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The evaluation and quantification of respirable coal and silica dust concentrations

A task-based approach

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ABSTRACT

Silicosis and coal worker's pneumoconiosis are serious occupational respiratory diseases associated with the coal mining industry and the inhalation of respirable dusts that contain crystalline silica. Silica exposure is an occupational health priority even when exposure has ceased or is below the occupational exposure limit (0.1 mg/m^3).

The objective of this study was to determine the individual contributions of the underground coal mining tasks to the total amount of respirable dust and respirable silica dust concentrations found in this environment. The tasks that were identified were continuous miner (CM) cutting, construction, the transfer point, tipping and roof bolting. Respirable dust sampling was conducted at the intake and return of each task, as well as at the intake and return of the section and the intake airway to the section. The five occupations that perform these tasks were also sampled to determine the personal exposure levels.

Respirable dust concentrations and small concentrations of respirable silica dust were found in the intake airway and intake of the section, indicating that the air that enters the section is already contaminated. The respirable dust-generating hierarchy of the individual tasks was: transfer point > CM right cutting > CM left cutting > CM face cutting > construction > roof bolting > tipping. For respirable silica dust the hierarchy was: CM left cutting > construction > transfer point > CM right cutting. CM face cutting, tipping and roof bolting generated concentrations of below quantifiable levels. The personal exposures also differed and the CM and stamler operators had the highest exposure to respirable dust (3.417 ± 0.862 mg/m^3) and respirable silica dust (0.179 ± 0.388 mg/m^3) concentrations, respectively. Recommendations have been included for lowering the respirable dust and silica dust concentrations that are generated and that the workers are exposed to underground.

Key words: respirable dust, respirable silica dust, coal mining

OPSOMMING

Silikose en steenkool werker se pneumokoniose is ernstige respiratoriese beroepssiektes wat geassosieer word met die steenkoolmyn industrie en die inasem van respireerbare stowwe met 'n kristallyne silika inhoud. Silika blootstelling is 'n beroepsgesondheidsprioriteit selfs al word blootstelling gestaak of onder die beroepsblootstellings limiet (0.1 mg/m^3) gehou.

Die doel van die studie was om vas te stel of die individuele bydrae van die take wat ondergrond in 'n steenkoolmyn uitgevoer word, ten opsigte van die totale respireerbare stof en silika konsentrasies wat in hierdie omgewing gegenereer word, van mekaar verskil. Die take wat geïdentifiseer is, is ononderbroke snywerk, konstruksie, oordragspunt, kanteling en vasbout van dakskroewe. Gravimetriese stof versamelings pompe is by die in – en uitlaat van elke taak en die seksie opgesit asook in die inlaat pad tot by die seksie. Die vyf beroepe is ook gemoniteer om die persoonlike blootstellingsvlakke te bepaal.

Respireerbare stof konsentrasies en klein konsentrasies respireerbare silika stof is in die inlaat pad en die inlaat van die seksie gevind wat aandui dat die lug wat die seksie binnegaan reeds gekontamineer is. Die hiërargie vir respireerbare stofgenerering van die individuele take was as volg: Oordragspunt > ononderbroke snywerk na regs > ononderbroke snywerk na links > ononderbroke snywerk aan die snyvlak > konstruksie > dakskroewe vasbout > kanteling; en vir respireerbare silika stof: Ononderbroke snywerk na links > konstruksie > oordragspunt > ononderbroke snywerk na regs. Ononderbroke snywerk aan die snyvlak, kanteling en dakskroewe vasbout het respireerbare silika stof onder die kwantifiseerbare vlakke gegenereer. Die persoonlike blootstellings het ook van mekaar verskil met die ononderbroke snywerk en kantelkar operateurs wat onderskeidelik die hoogste blootstellings aan respireerbare stof (3.417 ± 0.862 mg/m^3) en respireerbare silika stof (0.179 ± 0.388 mg/m^3) ondervind het. Voorstelle om die respireerbare stof en silika konsentrasies wat gegenereer word en waaraan die werkers blootgestel is te verlaag, is ingesluit.

Sleutelwoorde: respireerbare stof, respireerbare silika stof, steenkool myn

PREFACE

For the aim of this project it was decided to use the article format. The *Annals of Occupational Hygiene* journal was chosen as the potential publication and for that reason the whole dissertation is written according to the guidelines of this journal. The journal requires that references in the text should be inserted in Harvard style, and in the Vancouver style of abbreviation and punctuation in the list of references, with the list in alphabetical order by name of the first author.

A team of researchers contributed to the success, planning and completion of this study, and each of their contributions is listed in Table 1.

Table 1: Research team and their contributions

Researcher	Contribution
Mrs T. Grové	• Conducted personal, activity and environmental sampling. • Responsible for the literature research, statistical analysis and compiling of the dissertation and article.
Mrs T. van Dyk	• Supervised the study. • Assisted with the approval of the study protocol as well as the design, planning and compilation of the study. • Reviewed the dissertation and documentation and also assisted with the analysis and interpretation of the results.
Mr J.L. du Plessis	• Supervised the study. • Assisted with the study design, planning and compilation, reviewing of the dissertation, and documentation. • Helped with the interpretation of the results.
Miss A. Franken	• Assisted with the supervision. • Assisted with designing and planning of the study as well as reviewing the study's dissertation and documentation. • Assisted in the interpretation of the results.

The following statement from the supervisors confirms each researcher's role in the study:

> I declare that I have approved the article and that my role in the study as indicated above is representative of my actual contribution and that I hereby give my consent that it may be published as part of Tanya Grové's M.Sc. (Occupational Hygiene) dissertation.

Mr J.L. du Plessis

Mrs T. van Dyk

Miss A. Franken

LIST OF ABBREVIATIONS AND ACRONYMS

ACGIH	American Conference of Governmental Industrial Hygienists
BESR	Board on Earth Sciences and Resources
COAD	Chronic Obstructive Airway Disease
CM	Continuous Miner
COPD	Chronic Obstructive Pulmonary Disease
CWP	Coal Worker's Pneumoconiosis
DME	Department of Minerals and Energy
DOL	Department of Labour
HIV	Human Immunodeficiency Virus
HSE	Health and Safety Executive
IARC	International Agency for Research on Cancer
ILO	International Labour Organisation
MSHA	Mine Safety and Health Administration
NIOSH	National Institute for Occupational Safety and Health
NRC	National Research Council
NTP	National Toxicology Program

OEL	Occupational Exposure Limit
OSHA	Occupational Health and Safety Administration
PEL	Permissible Exposure Limit
PMF	Progressive Massive Fibrosis
PPE	Personal Protective Equipment
RDRP	Respiratory Disease Research Program
SIMRAC	Safety in Mines Research Advisory Committee
SORDSA	Surveillance of Work-related and Occupational Respiratory Diseases in South Africa
SiO_2	Silicon Dioxide
-SiOH	Silanol
TB	Tuberculosis
TWA	Time Weighted Average
TWA-TLV	Time Weighted Average-Threshold Limit Value
USA	United States of America
WCI	World Coal Institute
WHO	World Health Organisation

CHAPTER 1

GENERAL INTRODUCTION

CHAPTER 1

GENERAL INTRODUCTION

Traditionally mining is classified as either metalliferous or coal, and as either surface or underground mining. Metalliferous mining is also classified according to the commodity being mined, such as gold or platinum (Donoghue, 2004). Mining includes formal and informal operations, which have numerous and often a wide variety of airborne exposures, and accordingly cannot be seen as a homogenous industry.

Documentation stating the relationship between mining and occupational lung disease can be found as far back as the 1500s, when a description was made that dust with corrosive qualities was eating away the lungs and implanting consumption in the body (Ross & Murray, 2004). The commodities mined, airborne pollutant exposure levels, the period of exposure and co-existing illnesses or environmental conditions and lifestyle all have an effect on the relative frequency and severity of mining-related occupational lung diseases (Ross & Murray, 2004; Department of Labour, 2007). Even after mining operations and dust exposures are ceased, coal worker's pneumoconiosis (CWP), asbestos-related diseases, lung cancer and other occupational respiratory diseases, like silicosis, remain a high occupational health priority. Silica exposure also remains an occupational health priority, even when exposure is apparently below the legal occupational exposure limit (OEL) (Ross & Murray, 2004). The industries contributing the most to silica dust levels are the mining of metals, minerals and coal; the manufacturing of stone, clay and glass products; and also iron, steel and non-ferrous foundries (Finkelstein, 2000).

1.1 Problem Statement and Substantiation

There is a serious silicosis problem in South African coal mining industries that has its origin in the inadequate dust control and high disease rates that are found in the "silica industries" (Stanton *et al.*, 2006). The predetermined OEL for respirable coal dust is 2 mg/m^3 in South Africa, with due regard being given to the crystalline silica content of the dust (South Africa, 2006: 29276). The American Conference of Governmental Industrial Hygienists' (ACGIH) time weighted average-threshold limit value (TWA-TLV) for respirable crystalline silica is 0.025 mg/m^3 (ACGIH, 2008). The OEL for crystalline silica in South Africa is 0.1 mg/m^3 (South Africa, 2006: 29276).

The elimination of silicosis in South African mining industries is a very important priority and interventions have been initiated to achieve this goal, one of which includes a Safety in Mines Research Advisory Committee (SIMRAC) silicosis elimination control programme (SIM 030603) that was implemented in 2005. This programme has its focus on the containment and elimination of silicosis in the South African mining industry (Rees, 2005; Stanton *et al.*, 2006). Milestones for the suppression of silicosis were decided on at the Mine Health and Safety Summit in 2003 after regional and national workshops had been held between 2002 and 2004. These milestones are as follows (Stanton *et al.*, 2006):

- Ninety-five per cent of all exposure measurement results will be below 0.1 mg/m^3 by 2008; and
- No new cases of silicosis will occur amongst individuals that were not previously exposed, by 2013.

Internationally, silicosis has also caused some major concerns, and the International Labour Organisation (ILO) and World Health Organisation (WHO) have embarked on the "Global Elimination of Silicosis Campaign" (Fedotov, 1997). The International Institute for Occupational Safety and Health (NIOSH) has estimated that about 70% of all occupational disease deaths are caused by work-related respiratory diseases and cancers. For this reason, NIOSH has implemented a programme called the "Respiratory Disease Research Program" (RDRP), in this way providing leadership for the prevention of work-related respiratory diseases (NRC, 2008).

The identification of major dust sources or activities is one of the starting blocks for assessing occupational exposure to crystalline silica, where after workplace measurements follow as well as quantitative analysis of these samples and a comparison of the results with standards (Maciejewska, 2008).

1.2 Aims and Objectives

The primary aims of the study are to:

- Identify primary dust sources (activities) within the coal mining industry and then assess and rank (prioritise) these sources according to their contribution to the total amount of respirable dust and silica dust concentrations in the underground environment; and
- Quantify personal respirable coal and silica dust exposures.

1.3 Research Question

The study aims to answer the following research question:

Do different activities that are performed in the underground environment contribute differently to the total amount of respirable dust and silica dust concentrations found in this environment?

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CHAPTER 2

LITERATURE REVIEW

CHAPTER 2

LITERATURE REVIEW

All the information in this literature study is relevant, current, and important to this study. The literature study covers mining and, especially, information on the coal mining industry. Dust in total is also discussed, as well as coal and silica dust in particular, where after a discussion of the health effects caused by these types of dust follows. Legal requirements with regard to dust are also discussed as are control measures.

2.1 Mining Industry

2.1.1 Coal Mining

Coal is mined throughout the world and is classified as a fossil fuel. Two basic types of coal mining operations are found: surface and underground coal mining (Castranova & Vallyathan, 2000; Board on Earth Sciences and Resources (BESR), 2007).

For the selection of a suitable mining method a few factors have to be taken into consideration, such as the thickness of the coal seam, the depth and inclination of the coal seam, the nature of the roof and floor strata and also the amount of gas that is contained in the coal seam and the roof strata (BESR, 2007). In other words, the geology of the coal deposit is the main determining factor of the coal mining method chosen (WCI, 2005). Difficulties increase when extremely thick or thin seams are present and also when these seams are steeply inclined (BESR, 2007). A description of the different coal mining operations and their subdivisions follows.

During surface coal mining, the overburden (ground covering the coal seam) is removed first, in order to expose the coal seam for extraction (BESR, 2007). According to the World Coal Institute (WCI, 2005), surface coal mining is only economically viable when the coal seam is found near the surface. The broad steps in a surface mining operation are as follows (Anon., 2006; BESR, 2007):

- Remove topsoil and store it for later use;
- Drill and blast the strata that overlays the coal seam;

- Load and transport the fragmented burden material (soil);
- Drill and blast the coal seam itself;
- Load and transport the coal;
- Backfill with spoil and grade;
- Spread top soil over the graded area;
- Establish vegetation and ensure control of soil erosion and the water's quality; and
- Finally release the area for other purposes.

Some factors that provide challenging problems for designing stable slopes and productive operations are a steep topography and a steep dipping seam consisting of multiple seams. To decide which surface mining method should be used, the surface topography is taken into account. The different surface mining methods include contour mining, area strip mining or open pit mining (Anon., 2006; BESR, 2007).

The two underground coal mining methods are room-and-pillar mining (conventional and continuous) or longwall mining (WCI, 2005; Anon., 2006; BESR, 2007). Sixty per cent of the world's coal production is accounted for by underground coal mining (WCI, 2005).

Room-and-pillar mining consists of a set of entries, usually between three and eight, that are driven into a coal block and are connected by cross-cuts, usually at right angles to the entries, forming pillars (WCI, 2005; BESR, 2007). Commonly, these entries are spaced from approximately 15 m to 30.5 m apart and the cross-cuts are about 15 m to 45 m apart (BESR, 2007). The pillars may then also be extracted, by means of 'retreat mining', or they can be left standing, but this depends on the mining conditions. Retreat mining occurs when the coal pillars are mined as the workers retreat and the roof is allowed to collapse and then the mine is abandoned (WCI, 2005; BESR, 2007). These pillars can account for about 40% of the total coal in the seam (WCI, 2005).

Room-and-pillar mining is the most common method of underground coal mining and can be further divided into conventional room-and-pillar mining and continuous room-and-pillar mining (Anon., 2006; BESR, 2007). Several pieces of equipment are used in the conventional room-and-pillar method. The operations performed in conventional room-and-pillar coal mining are drilling, undercutting, blasting, loading and roof bolting and these are performed in sequence to extract coal at the working face. A mechanical machine, the continuous miner (CM), replaces all the unit operations of the conventional room-and-pillar mining method in the continuous room-and-pillar mining method. All the cutting and loading functions are performed by the CM (BESR, 2007). In both room-and-pillar methods, coal is loaded onto coal transport vehicles (shuttle cars/stamlers), where after it is dumped onto a panelbelt conveyor to be transported to the outside of the mine (Anon., 2006; BESR, 2007). After the coal has been cut, roof bolts are used to support the strata above the coal seam that has been hollowed out (WCI, 2005; BESR, 2007). When conditions are favourable, the production from a continuous mining section can be above 800 000 tons per year per CM. Room-and-pillar continuous mining is used even in mines where the longwall method is the principal extraction method, when it is economically possible (WCI, 2005; BESR, 2007). The developments of the mine and the longwall panels are then both performed by means of the continuous room-and-pillar method (BESR, 2007).

Longwall mining is characterised by high recovery and extraction rates and is seen as an automated form of underground coal mining (BESR, 2007). This method can only be performed in relatively flat-lying, thick and uniform coal beds; for this reason, careful planning is needed before this method is chosen. The mechanical shearer, a high-powered cutting machine, is the machine used in this method of underground coal mining (WCI, 2005; BESR, 2007). The shearer passes over the exposed face of coal, and then shears away broken coal, which is continuously hauled away by a floor-level conveyor system. This mining method extracts all the machine-minable coal between the floor and ceiling that is in an adjoining block of coal (a panel) and no support pillars are left behind within this panel area (BESR, 2007). The roof is held up temporarily by self-advancing hydraulically powered supports while the coal is extracted, after which the roof is allowed to collapse (WCI, 2005; Anon., 2006). To justify the capital cost of longwall equipment, large coal reserves are required (BESR, 2007). The recovery rate of longwall mining is around 75% (WCI, 2005, Anon., 2006).

2.1.2 Airborne Dust Sources

The main coal mining activities that are sources of dust are blasting, drilling, cutting and transportation (Stanton *et al.*, 2006). The WCI (2005) also states that dust at coal mining operations can be the result of: trucks that are driven on unsealed roads, coal crushing operations, drilling operations and also wind blowing over areas that are disturbed by mining operations.

Face production activities in conventional coal mining are major dust sources (Stanton *et al.*, 2006). The two highest dust-generating sources are coal cutting and roof bolting (Kissell &

Goodman, 2003; Stanton *et al.*, 2006; Goodman, 2009). When no dust suppression system, such as wet drilling or a dust extraction system, is present roof drilling may also be a major quartz dust source (Stanton *et al.*, 2006).

Dust generated by the roof bolter is usually the result of a malfunctioning dust collector, which results in dust escaping (Kissell & Goodman, 2003). When the dust collector box has not been properly cleaned, it is also a potential source of dust to the roof bolter personnel (Goodman & Organiscak, 2002). High dust exposures of workers on roof bolters can also be the result of the CM working upwind of the roof bolter (Davitt, 2008; Kissell & Goodman, 2003; Pollock *et al.*, 2009). Pollock *et al.* (2009) in their research into dust exposures and mining practices in mines in the Southern Appalachian region observed inadequate ventilation at the bolter faces of some of the mines they surveyed. They recommended that the line curtains (sails that are hung like curtains to direct the ventilation) be used to direct the air through the working area in order to reduce the dust concentrations in this area. Where mines had properly installed and anchored these curtains, lower exposure to the miners was observed. The lack of ventilation at the roof bolter faces is a serious problem, especially if the roof bolter spends most of the time during the shift working downwind of the CM.

Cutting the coal generates the most airborne coal dust and this is why well-functioning ventilation systems, water supply, spray systems and an on-board scrubber are so important (Kissell & Goodman, 2003:23-38; Stanton *et al.*, 2006). Because the working position of the CM operator is on or near the CM, this person is frequently exposed to the greatest concentrations of respirable dust (Goodman *et al.*, 2000). The CM consists of a cutting drum at the front of the machine, with bits (big sharp-pointed drill points) covering the drum. These bits cut the coal surface when the drum spins during production. The coal face is impacted by the cutting bits, which tear the coal from the face and then crush it under high normal forces that are imposed by the cutting bits.

The condition of the cutting bits determines the depth of the cut, and when these bits are worn they increase the amount of dust generated (Khair *et al.*, 1999; Stanton *et al.*, 2006). This causes the scrubber maintenance to become a problem, resulting in large amounts of dust being made airborne (Pollock *et al.*, 2009). The life of these bits depends on the nature of the rock, and when severe rock conditions are encountered the cutting bit life is drastically reduced (Pollock *et al.*, 2009). The bits have carbide tips and when the bits become worn below these tips they grind rather than cut, generating increased levels of airborne dust, and they also become very hot, causing frictional heat (Pollock *et al.*, 2009; Stanton *et al.*, 2006). Pollock *et* *al.* (2009) recommend that attention be given to worn bits, clogged water sprays and scrubber maintenance every time the CM is relocated to another cut.

Respirable dust particles can also adhere to the cut coal and these particles become dislodged and airborne as a result of the handling of the coal after it has been cut. Points at which coal is handled include the landing point on the CM, the transfer point from the CM to the shuttle car, the belt loading point (from the shuttle car to the conveyor belt) and also all the belt transfer points that follow (Stanton *et al.*, 2006). High dust levels seen at the remote operator of the CM are usually the result of the positioning of the operator, who might, for example, not be spending enough time in front of the blowing line curtain (Kissell & Goodman, 2003; Pollock *et al.*, 2009). When high downwind dust levels are present at the CM, a dirty scrubber may be the cause (Kissell & Goodman, 2003). Dust roll-back is also a reason for high dust exposures observed at the CM operator (Goodman *et al.*, 2000; Pollock *et al.*, 2009).

Blasting operations can also be a major source of dust (Kissell & Stachulak, 2003: 83-96). While blasting is taking place all workers are removed from the site, and only return after the face area has been cleared of dust and harmful gasses by the ventilation system. During a blast a short period of high dust concentration is present (Stanton *et al.*, 2006).

Away from the face area, the primary sources of dust generation include conveyor belts, coal haulage transfer points and the haulage roads (Kissell & Stachulak, 2003: 83-96; Stanton *et al.*, 2006).

Dust that adheres to conveyor belts can become airborne by means of the vibration experienced on the belt that is caused when the conveyor belt moves over the belt rollers. Dust can also stick to the bottom of the belt where it can be crushed and pulverised, which creates a great deal of respirable dust (Goldbeck & Marti, 1996; Swinderman *et al.*, 1997; Stanton *et al.*, 2006).

Examples of transfer points include: from the feeder breaker to the conveyor belt, from the stage loader to the conveyor belt, from one conveyor belt to another, from the conveyor belt to transfer chutes, and from the belt to the silos. Dust can be generated at all these transfer points.

Most of the haulage roads are situated in the clean intake that leads into the mine and to the sections inside the mine and for this reason dust in or on these roads is a substantial problem. When the dust particles are big and coarse they will settle out, but the vehicles' tyres will crush these particles, causing them to stay airborne and creating a significant dust source in the intakes. This dust source can, however, be treated with a binding agent that binds the dust and prevents it from becoming airborne (Stanton *et al.*, 2006).

In the longwall underground coal mining method, the shearers/plows, stage loader/crusher and the movement of the roof supports are the major dust sources (Stanton *et al.*, 2006). Kissell *et al.* (2003:39-55) add that the intake is another major dust source in longwall mining. The seam conditions, operational parameters and types of internal and external water sprays that are operating determine the amount of airborne dust produced by the shearer. A few factors also determine the amount of airborne dust generated by the roof supports, of which the most important is the immediate roof conditions. These conditions also vary with the support advancing operation as well as the setting and yielding loads of the supports. The greater the amounts of dust generated, the more the setting and yielding loads increase. A roof fall in the goaf area, where the deliberate collapse of the seam roof and pillars occur, is also a source of dust generation. In this case, the amount of dust generated and dispersed into the air depends mostly on the size of the fall (Stanton *et al.*, 2006).

Major dust-generating sources in surface coal mines are drilling, blasting and primary crushing at tips (Stanton *et al.*, 2006). Most of the respirable dust that affects the workers is generated by overburden drilling (Organiscak *et al.*, 2003:73-81). Dusty operating loaders, shovellers, dozers, draglines and haul trucks also generate dust. This is mainly the case in dry and windy conditions (Organiscak *et al.*, 2003:73-81; Stanton *et al.*, 2006). Other sources are the dust on the roadways and around stockpiles and loading operations, and then also where secondary crushing or screening takes place (Stanton *et al.*, 2006).

Dust generation in quarrying is found at all stages of the production process. Main risk areas in the hard rock sector include: areas where exploratory drilling and drilling at the face take place, roads and also the crushing plant where the higher risk occupations are drillers, the plant operator and the maintenance operator. Quarrying operations in monumental stone and slate produce dust from hand-operated drills, portable hand-operated saws as well as from splitting and dressing (Stanton *et al.*, 2006).

Among miners, silica exposure is quite common, although it is highly variable because it is dependent on the silica content of the ore (Steenland & Stayner, 1997; Pollock *et al.*, 2009). When mixed dusts are breathed in, low exposures may occur, and exposure levels of the general population are not seen as sufficient to cause disease (Steenland & Stayner, 1997). Underground exposures to silica dust usually occur during the drilling of rock, transportation of workers or materials and the loading of mine materials. Workers most likely to be exposed to the highest concentration of silica dust are miners that operate equipment such as locomotives, CMs, and roof bolters, and those miners that drive shuttle cars. Those workers working downwind of the aforementioned activities and equipment also have a high probability of exposure. In underground coalmines, all employees are at risk of being exposed to dust that contains silica that is part of the coalmine dust (Davitt, 2008). Goodman (2009) mentions that the CM operator and the roof bolt operator are the two occupations with the highest risk of excessive exposure to respirable silica dust. In an ongoing study conducted by NIOSH researchers on silica dust exposure in underground mining the data indicated an increase in the respirable silica dust in the roof bolter intake. The amount of time that the roof bolter works downwind from the CM should be controlled to limit exposure (Goodman & Organiscak, 2002).

2.2 Airborne Particles: Dust

Dust is defined as the generation of solid particles that are dispersed into the air by means of handling, crushing and grinding of organic or inorganic materials, which include rock, ore, metal, coal, wood or grain (Stanton *et al.*, 2006). The definition of dust, according to the Mine Safety and Health Administration (MSHA), is: finely divided solids that may become airborne from their original state without any chemical or physical change, other than fracture (MSHA, 2008). During the above-mentioned dust-generating processes, different particle sizes are produced. Some particles remain in the air indefinitely because of how small they are, whilst others are too large to remain airborne and they settle. Dust sizes are measured in micrometers, commonly written as microns (Occupational Health and Safety Administration (OSHA), 1987; Stanton *et al.*, 2006).

Among the industries that contribute the most to atmospheric dust levels are construction, agriculture and mining. In operations where minerals are processed, mining dust is emitted through breaking of the ore by impact, abrasion, crushing and grinding. The release of dust that was previously generated during loading, dumping and transferring operations is also a source of mining dust. The recirculation of dust that was previously generated by wind or the movement of workers and/or machinery can cause dust exposure as well. The physical characteristics of the material and the way in which the material is handled determine the amount of dust emitted by these activities.

Dust is found in many types, of which fibrogenic dust is one and this includes dusts such as free crystalline silica or asbestos. These dusts are biologically toxic and can form scar tissue and impair lung functioning ability when they are retained in the lungs. Nuisance dust is usually dust with less than 1% quartz, which therefore has little adverse effect on the lungs, as reactions to nuisance dusts are usually reversible, other than reactions to fibrogenic dusts (OSHA, 1987).

2.2.1 Classifications of Dust

Dust can be divided into three primary categories, according to particle size: respirable dust, inhalable dust and total dust (OSHA, 1987).

Respirable dust is dust of which the particles are very small, i.e. less than 10 microns (µm) in diameter (Stanton *et al.*, 2006; OSHA, 1987). Per definition, respirable dust is dust that contains particles that are small enough to enter the gas exchange region of the human lung, and are less than 10 µm in aerodynamic diameter in accordance with the ISO/CEN curve (SKC, 2005). These particles are likely to be retained, as they are generally beyond the natural clearance systems of the body, in other words the cilia and mucous in the respiratory tract (OSHA, 1987). The defence mechanisms of the lungs can still remove particles that reach the airway walls in the tracheobronchial tree, but approximately 30% of the particles, in the range of one to three microns, will be deposited in the lung tissue itself (White, 2001). Silica dust and coal dust can be classified as respirable dust (Health and Safety Executive (HSE), 2002; Belle & Stanton, 2007). These fine dust particles that contain free silica pose a major risk and concern, for the main reasons that (HSE, 2002):

- These particles are invisible to the naked eye under normal lighting conditions;
- These respirable particles can, for extended periods of time, be airborne in a person's breathing zone; and
- After inhalation, these particles penetrate, or can penetrate, to the lungs and exert their effects here.

Dust particles classified as inhalable dust can be deposited in the respiratory tract after their entrance through the mouth and nose during breathing. These dust deposits in the respiratory tract may accumulate in the sputum or mucus and in this way be swallowed to be absorbed in the digestive system, or they may be coughed out and back into the air (Belle & Stanton, 2007). These particles are usually smaller than 50 µm in aerodynamic diameter (Burrows *et al.*, 1989).

Total dust can then be classified as dust that consists of all airborne particles, regardless of size and/or composition; thus, total dust is a combination of all the dust types (OSHA, 1987). Total dust particles are not selectively collected in terms of their particle size and they may cause toxic effects when they are inhaled in large quantities (MSHA, 2006).

Another classification of dust also exists, which is known as "thoracic fraction". Dust particles that are smaller than 30 µm can be classified as the thoracic fraction, and the reason that they are hazardous is that they can be deposited anywhere in the alveoli and/or lung airways. No thoracic OELs have yet been established by the Department of Minerals and Energy (DME) and the Department of Labour (DOL) (Belle & Stanton, 2007; HSE, 2002).

2.2.2 Coal Dust

2.2.2.1 Composition, characteristics and types of coal dust

The WCI (2005) defines coal as a fossil fuel and a combustible, sedimentary, organic rock that is mainly composed of carbon, hydrogen and oxygen. The oxides of coal dust, as well as its mineral contents, vary between different seams. Smaller quantities of nitrogen and sulphur are found in coal dust and in all cases mineral matter is found in coal dust that remains ash when it is burnt. A small proportion of quartz or silicates, usually less than 5%, is found in respirable coal mine dust and these particles are mostly found in the dirt bands within the coal stratum. According to the report of the SIMRAC Project GAP 802 of 2003, the average measured silica content of coal seams in South Africa was 3.5% (Biffi & Belle, 2003). When the overburden is removed by the miners or when they tunnel through rock to get to the coal that has to be mined, elevated silica exposures may occur (Stanton *et al.*, 2006). When coal matures from peat to anthracite, the process is known as "coalification" and this process has important influences on coal's physical and chemical properties, and hence the rank of the coal (WCI, 2005). The coal rank sequence is as follows: anthracite (86-98% carbon content) has a higher rank than that of bituminous (45-86% carbon content), which is followed by sub-bituminous (35-45% carbon content) and lignite (25-35% carbon content) (Ross & Murray, 2004). Anthracite is sometimes referred to as "hard coal", as it is hard, black and lustrous and has a low sulphur content, low moisture content and produces more energy. Bituminous coal is a black, hard and dense coal, with bands of bright and dull material often found in it. Lignite is a soft brownish-black coal, with a high moisture content; it can also be called "brown coal". Sub-bituminous coal, which is also called “black lignite”, has a slightly lower moisture content than lignite (American Coal Foundation, 2005; WCI, 2005).

Coal dust from opencast mining and underground mining differs as a result of the different mining processes, although these dusts are also highly heterogeneous. In underground mining, the coal itself is being cut, as the underground coal seams are followed by the different underground mining methods. In opencast coal mining, the overburden and the rock strata that cover the coal seams are removed. The result is that there is a much higher mineral content in surface coal mining than there is coal content, where the opposite is found in underground coal mining. Thus, opencast coal dust is dominated by mineral grains and is often referred to as “*shale* dust” (Reynolds *et al.*, 2003). The most significant coal dust sources are found in the underground coal mines where mining operations generate large amounts of dust. The underground coal miners are exposed to higher levels of coal dust than surface mine workers because of the large amounts of coal dust found in these environments. Coal dust in surface or strip coal mines is diluted by outdoor air; however, one occupation associated with a greater risk of developing silicosis in surface coal mines is rock-drilling (Castranova & Vallyathan, 2000).

2.2.2.2 Toxicity of coal dust

The inhalation of particulate matter during the coal mining process is the main cause of human disease associated with coal mining. Cases have been reported where coal that contains arsenic, fluorine, selenium and mercury has adversely affected human health (Finkelman *et al.*, 2002). Coal mine dust inhalation can lead to the development of several diseases, namely coal worker’s pneumoconiosis (CWP) (simple or complicated), chronic bronchitis, emphysema, Caplan Syndrome (rheumatoid pneumoconiosis), progressive massive fibrosis (PMF), lung function loss and also silicosis (Schins & Borm, 1999; Castranova & Vallyathan, 2000).

2.2.3 Silica Dust

2.2.3.1 Composition, characteristics and types of silica dust

The formation of silica occurs naturally and is quite common. Silica is a compound, as it consists of the two elements silicon and oxygen, and is also known as “silicon dioxide” (SiO_2). Silicon and oxygen exist naturally and are the most widespread elements in the earth’s crust, and together these two elements make up approximately 75% of the earth's crust (Lujan & Ary, 1992; Stanton *et al.*, 2006). Silicon dioxide crystals are tiny, very hard, translucent and colourless when in their natural and pure form (Montana Department of Labor Industry, 2002).

Silica is a major natural component of sand, quartz, granite and mineral ores (Lujan & Ary, 1992; Montana Department of Labor Industry, 2002; Rees & Murray, 2007). Silica can be found in a crystalline or cryptocrystalline form, is harmless in this form and cannot be inhaled. In contrast, when silica dust is generated, for example through construction activities, it can be inhaled by workers (Larson, 2004; Maciejewska, 2008). Silica dust exposure is considered as hazardous as exposure to asbestos to human health (Larson, 2004).

Silicon is referred to as a "metalloid" by some scientists, as it is classified as a non-metal but still possesses some properties that are associated with metals. One of the properties associated with silicon is its unusual electrical capability: Silica can be a semi-conductor; in other words, at high temperatures it acts like a metal and conducts electricity, but at low temperatures it does not conduct electricity and acts like an insulator (Lujan & Ary, 1992). Richerson (2006) contributes to the above by stating that quartz crystals have pizo-electric behaviour in a particular crystal direction, and until today natural quartz crystals are mined and then sliced into devices such as oscillators.

Tiny organisms can also produce silica; hence, silica also has a biological origin. These tiny organisms are diatoms (plants) and radiolarians (animals), which both extract silica from the water that surrounds them, to form their structures or shells. Silica is a nutrient for these organisms that they need for survival. The above indicates that silica can be found in more than one state, namely amorphous (non-crystalline) and crystalline. "Amorphous" refers to the remains from a diatom and "crystalline" refers to the quartz crystal and is found in numerous forms. Both the amorphous and crystalline forms are silica, but they differ physically (Lujan & Ary, 1992). The physical difference is in their molecular orientation. Crystalline refers to a fixed pattern of the molecules, whereas amorphous refers to a non-periodic, random molecular arrangement (Lujan & Ary, 1992; Stanton *et al.*, 2006).

Polymorphs are different forms of an existing compound and crystalline silica has seven different forms (polymorphs). The most common of these forms is quartz and the other two most common forms are tridymite and cristobalite, which are all stable at different temperatures (Lujan & Ary, 1992; Montana Department of Labor Industry, 2002). The four remaining polymorphs are extremely rare. Quartz is further subdivided into beta and alpha quartz, which are each stable under different thermal temperatures (Lujan & Ary, 1992).

Quartz, even if in just trace amounts, is found in all soils and is also the major component of sand and dust in the air (Lujan & Ary, 1992; Davitt, 2008). If there is more than 47% silica in a rock, the rock contains quartz (Department of Labour, 2007). Rock types abundant with quartz are igneous rock (12%), metamorphic rock and sedimentary rock. The earth's crust (lithosphere) is composed of the above-mentioned three types of rock and the lithosphere continually undergoes changes between these types of rock. A rock cycle exists between ingneous, metamorphic and sedimentary rock. Activity (heat and pressure) beneath the earth's crust is reflected by igneous rocks. Metamorphic rock reflects the activity both beneath the crust as well as within and at the surface. The conditions at the earth's surface, such as wind and ice, are reflected by sedimentary rocks. Passing of geologic time may cause sedimentary rocks to be altered by heat and then create metamorphic or igneous rock. In turn, all rocks may also be eroded to produce sediments. These sediments can then, in turn, lithify (harden) into sedimentary rocks. Quartz endures all these changes and is known as one of the Earth's harder materials as well as one of its primary building blocks (Lujan & Ary, 1992).

The transformation of quartz when it is heated is also of importance, as this changes the crystalline structure, and this transformed crystalline structure is usually more pathogenic or toxic than the original alpha quartz crystalline structure (Department of Labour, 2007; Rees & Murray, 2007). Geologists have noted that quartz changes from one form to the other at a temperature of 573 °C (Lujan & Ary, 1992). Conditions for this transformation can be found in foundry processes, the burning of waste materials and other manufacturing procedures. Alpha (low) quartz is the most common, naturally found, form of quartz (Lujan & Ary, 1992, Davitt, 2008). This is also the type of silica that is mostly released during mining, blasting and construction activities. Crystobalite is usually formed during the processing of crude materials that involves heating to high temperatures (Department of Labour, 2007).

Silicates are also a source of silica (usually less than 1%) and they are compounds of silicon and oxygen plus other elements. Bonding of silicon and oxygen with other elements takes place in a paired formation that is called "silicon-oxygen (SiO_4) tetrahedron", because it consists of one silicon atom and four oxygen atoms (Lujan & Ary, 1992; Montana Department of Labor Industry, 2002; Richerson, 2006). This silicon-oxygen tetrahedron most frequently bonds with sodium, potassium, calcium, magnesium, iron and aluminium to form silicates. Examples of silicates include mica, soapstone, talc, trembolite and Portland cement. Silicate materials are regarded as the basic materials out of which most rocks are created (Lujan & Ary, 1992; Montana Department of Labor Industry, 2002).

2.2.3.2 Toxicity of silica dust

A few factors influence the potential and toxicity of crystalline silica for inducing fibrosis (Stanton *et al.*, 2006; Department of Labour, 2007). These are mainly the biological activity of the type of crystalline silica, the particle size, as well as whether the coal is freshly cut or if it has "aged".

The forms of crystalline silica that have the highest potential for inducing fibrosis are quartz, cristobalite and tridymite (Mossman & Churg, 1998; Castranova & Vallyathan, 2000; Department of Labour, 2007). Each of these has a different structure and that causes differences in their biological reactivity (Castranova & Vallyathan, 2000; Department of Labour, 2007). Tridymite has a bigger potential for inducing fibrosis than does cristobalite and, in its turn, cristobalite has a bigger potential than quartz (Mossman & Churg, 1998).

Proof also exists that freshly fractured quartz has an increased potential for inducing a fibrotic reaction in the lungs as opposed to the potential of "aged" quartz (Schoeman & Schröder, 1994:70, Stanton *et al.*, 2006; Department of Labour, 2007). When the rock is fractured, radicals are present on this fracture surface and this is primarily the determinant of toxicity. A radical is an atom or group of atoms with at least one unpaired electron that will stabilise itself by stealing an electron from a nearby molecule and binding to it. When the radicals are decayed, the potential of the quartz particle for inducing fibrosis is reduced. The presence of -SiOH groups (silanol groups) on the crystalline silica surface, when it is hydrated, presents the capability of the formation of hydrogen bonds with membrane components and these hydrogen bonds cause membrane damage in the lungs and consequently disruption of cellular integrity. Also, the presence of aluminium and iron on the mineral pattern of the crystalline structure of "aged" quartz seems to make the particle less fibrotic (Stanton *et al.*, 2006; Department of Labour, 2007).

The size of the particle also plays an important role in terms of toxicity (Department of Labour, 2007). The reason for this is that the respirable silica particles are small enough to reach the alveoli or gas exchange areas of the lungs (White, 2001; Stanton *et al.*, 2006). Particles with sizes of above seven microns will be trapped in the nasal passages, whereas particles below this size will be let through to the lung's gas exchange region (White, 2001). A further discussion follows later under 5.1 Silicosis.

2.3 Legislation

A permissible exposure limit (PEL) of 0.1 mg/m^3 for an eight-hour time weighted average (TWA) exposure to respirable crystalline silica has been set by the United States Occupational Safety and Health Administration (OSHA, 2006). The National Institute for Occupational Safety and Health (NIOSH) has recommended an exposure limit of 0.05 mg/m^3 for exposure to respirable crystalline silica as an eight-hour TWA for up to ten hours a day during a 40-hour work week (NIOSH, 2002). The ACGIH TWA-TLV for respirable crystalline silica is 0.025 mg/m^3 (ACGIH, 2008). The OEL for respirable crystalline silica in South Africa, including cristobalite, quartz and tridymite, is 0.1 mg/m^3 (South Africa, 2006:29276).

According to South Africa (2006:29276), the occupational exposure limit (OEL) for respirable coal dust is 2 mg/m^3, due regard being given to the crystalline silica content of the dust. In the United Kingdom, the Coal Mines (Control of Inhalable Dust) Regulations 2007 state that the occupational long-term exposure limit for respirable coal dust is 2 mg/m^3 over an eight-hour TWA. In the United States of America (USA), the Occupational Safety and Health's (OSHA, 2006) PEL for coal dust (greater than or equal to 5% silica) is 10 mg/m^3/SiO_2 x 2 for an eight-hour TWA, whereas the ACGIH has assigned a threshold limit of 0.1 mg/m^3 for an eight-hour TWA or a 40-hour work week for the same class of coal. Coal dust's (greater than or equal to 5% silica) toxicity is considered to be similar to that of quartz by the ACGIH (ACGIH, 2008). The United States Federal Coal Mine Health and Safety Act of 1969 limits personal exposure to respirable dust to 2 mg/m^3, measured gravimetrically as an eight-hour TWA concentration of respirable coal dust. When more than 5% silica is present on the sample by weight, the respirable dust standard is reduced with the formula "10 divided by the percentage silica". The 2 mg/m^3 standard with a silica percentage of 5% corresponds to a personal exposure limit for silica of 1 µg/m^3.

2.4 Dust Controls

Dust can be controlled by applying engineering principles that are properly designed, maintained and operated. The three major approaches for reducing employee dust exposure are prevention, control systems and dilution or isolation (OSHA, 1987). Kissell (2003: 3-22) also states that the three major dust control methods are ventilation, water and then dust collectors.

Exposure of dust emissions cannot be prevented totally, but, when material handling components work properly, there is likely to be a reduction in generation, emission and dispersion (OSHA, 1987). Kissell (2003: 3-22) supports this by writing that the reduction of the generation of dust is the most important step, as it is always harder to control dust once it is airborne.

With dust collection systems, the dust is collected at the source and transported to a dust collector. The dust is thus captured before it becomes airborne (OSHA, 1987; Kissell & Goodman, 2003: 23-38).

Wetting is extremely important for dust control and this method has two focuses: to wet the broken material that is to be transported and to capture airborne dust (Kissell, 2003: 3-22). Using wet dust suppression systems causes the dust to stay moist and in this way immobilises the dust so very little of it becomes airborne (OSHA, 1987; Kissell, 2003: 3-22). Airborne dust capture through water sprays implies that airborne dust is suppressed by means of spraying fine water droplets on a cloud of dust. The water and dust agglomerate and become too heavy to remain airborne and the result is that they settle and leave the air stream (OSHA, 1987; Kissell, 2003: 3-22; Stanton *et al.*, 2006). Water sprays are situated on the continuous miner (CM), used in continuous room-and-pillar mining, to suppress the dust directly at the cutting site by spraying as the CM drum turns and cuts the coal face (Stanton *et al.*, 2006).

Local ventilation methods include both dilution and displacement ventilation (OSHA, 1987; Kissell, 2003: 3-22). In dilution ventilation, the air is cleaned by diluting the contaminated air with uncontaminated air by bringing clean, fresh and uncontaminated air into the mine or section, diluting it in the section and returning the contaminated air out of the mine or section (OSHA, 1987; Stanton *et al.*, 2006). Basically more air is provided to dilute the dust (Kissell, 2003: 3-22). Displacement ventilation is a way of confining the dust source and keeping it away from the workers by situating the workers in such a way that they are upwind of the dust (Kissell, 2003: 3-22; Stanton *et al.*, 2006). This method is used commonly in CM faces, as the remote control for the CM allows the CM operator to stand in the fresh air intake (Kissell, 2003: 3-22). Isolation ventilation is an example of displacement ventilation. Following this method, the workers are isolated from the contaminated area by being placed in an enclosed cab that is supplied by clean, fresh and filtered air (OSHA, 1987; Kissell, 2003: 3-22).

Wetting agents have also received some attention over the years, especially in coal mines (Kissell, 2003: 3-22). Wetting agent effectiveness seems to depend on the type of wetting agent, type of coal, dust particle size, dust concentration, water pH and water mineralogy (Hu *et al.*, 1992; Tien & Kim, 1997; Kissell, 2003: 3-22).

The prevention of silicosis would be successful if proper primary and secondary prevention strategies were applied (Department of Labour, 2007). Proper ventilation, dust collectors, wetting techniques, substitutes for quartz-containing materials and the wearing of personal protective equipment (PPE) are some examples of primary prevention strategies (Weissman & Wagner, 2004; Department of Labour, 2007). The use of proper and approved PPE, such as respirators, the training of the workers and also the use of medical examinations are very important in prevention of exposure (Weissman & Wagner, 2004). The reduction and avoidance of the inhalation of crystalline silica dust make up the best preventative strategy. Training provided to workers and management, such as respirator training, is of the utmost importance as another mechanism for preventing silicosis (Department of Labour, 2007).

Secondary prevention includes monitoring the exposed workers regularly by means of serial chest radiographs and spirometry. The ideal would be to remove the subjects with silicosis from the source of exposure completely (Weissman & Wagner, 2004).

Since the 1900s there has been a marked decrease in silica exposures and silicosis over time, mostly because dust controls were applied in most job sites as silicosis was recognised as an occupational disease in this time (Steenland & Stayner, 1997; Weissman & Wagner, 2004).

2.5 Occupational Respiratory Diseases

Common occupational lung diseases that are characterised by fibrotic nodular lung lesions caused by the inhalation of occupational dusts, such as coal dust and crystalline silica dust, are CWP and silicosis, both associated with mining activities in South Africa (Wang *et al.*, 2005). Exposure to airborne coal mine dust creates the risk of workers developing CWP, silicosis, PMF as well as other diseases, collectively known as "chronic obstructive pulmonary disease" (COPD). COPD is also known as "chronic obstructive airway disease" (COAD) (Stanton *et al.*, 2006). The total dose and intensity of dust exposure are the determining factors of the severity of these diseases (Wang *et al.*, 2005). Both silicosis and CWP are forms of pneumoconiosis, which refers specifically to lung disorders caused by the inhalation of dust (OSHA, 1987; Stanton *et al.*, 2006; Department of Labour, 2007).

2.5.1 Silicosis

As stated above, silicosis is defined as a form of pneumoconiosis and as a disease resulting from exposures to high levels of respirable silica dust; it is irreversible and not curable (OSHA, 1987; Stanton *et al.*, 2006; Department of Labour, 2007).

Inhaled air passes through the upper airways, which consist of the trachea, bronchi and smaller airway branches, and eventually reaches the bronchioles. Airborne dust particles that are inhaled are then exhaled or deposited in the upper airways and removed by the mucociliary escalator. Clusters of alveoli are found beyond the respiratory bronchioles and at this location the exchange between oxygen and carbon dioxide takes place. The alveolar air spaces have very thin walls which are particularly vulnerable to airborne substances (Stanton *et al.*, 1999). Particles that are inhaled and have an aerodynamic diameter of less than 10μm (as is characteristic of respirable silica dust) can be deposited in the areas of the respiratory bronchioles and in the alveoli (Stanton *et al.*, 1999; White, 2001). The respirable dust particles accumulate in the alveolar regions of the lungs when free crystalline silica exposure's intensity and duration is too high and the alveolar macrophages cannot clean the lungs as effectively as they usually do. This is mainly due to the toxicity of the inhaled respirable free crystalline silica dust particles and their accumulation. Formation of focal deposits that contain a large number of fibroblasts and interlacing reticulin is usually the result, and these focal deposits then develop into masses of interlacing collagen fibres (Schoeman & Schröder, 1994:70; Department of Labour, 2004).

Silicosis is characterised by the scarring of lung tissue, and the lung's ability to exchange oxygen with waste gasses produced in the body is reduced subsequently (Stanton *et al.*, 2006; Department of Labour, 2007).

All the above-mentioned changes in the lungs and their functionality increase the person (or worker's) susceptibility to other infections, such as tuberculosis (TB), and lower his or her pulmonary tissue's resistance to mycobacteria (Schoeman & Schröder, 1994:70; Stanton *et al.*, 2006). The disease induced by free silica exposure is fibrotic pneumoconiosis, whereas the lung disease caused by crystalline silica exposure is known as "silicosis" (Department of Labour, 2007).

Silicosis is also known to be a slowly progressive disease, and the development of silicosis generally takes more than ten years (Ross & Murray, 2004; Department of Labour, 2007). After exposure to respirable silica dust has been ceased, the disease may continue to progress. Most miners develop radiological signs of silicosis when they are older than 50 years. The type of silicosis a worker will develop mainly depends on the worker's level of exposure, although freshly fractured silica, admixtures of other minerals and peak exposures may also play a role (Ross & Murray, 2004; Rees & Murray, 2007; Department of Labour, 2007). Three main categories of silicosis exist: acute, accelerated and chronic silicosis (Castranova & Vallyathan, 2000; Department of Labour, 2007). Silicosis may also develop into conglomerate silicosis (Castranova & Vallyathan, 2000). A discussion about these different categories follows.

2.5.1.1 Chronic silicosis

Chronic silicosis is the most commonly found form of silicosis (Montana Department of Labor Industry, 2002; Ding *et al.*, 2002; Rees & Murray, 2007) and can be subdivided into two categories: simple (nodular) and complicated (PMF or conglomerate) silicosis. In its early stages, chronic silicosis may go undetected for years. Fibrotic changes (silicotic nodules) in the lung occur with chronic silicosis, which usually appears after ten to 30 years of excessive inhalation of silica dust (Stanton *et al.,*1999; Rees & Murray, 2007). Abnormalities may only be revealed on chest x-rays after 15 to 20 years of exposure under these conditions (Stanton *et al.,*1999; Montana Department of Labor Industry, 2002). The fibrotic changes in the lung are caused by the accumulation of the silica dust in the lungs and these changes still occur even after exposure has been ceased (Stanton *et al.,*1999; Montana Department of Labor Industry, 2002; Rees & Murray, 2007). The nodules are usually found in the upper lobes, but, as the disease progresses, they may be found in the mid- and basal zones (Rees & Murray, 2007). Chronic silicosis is brought on by low, but frequent silica dust exposure, where the dust contains 18-30% crystalline silica (Stanton *et al.*, 2006; Department of Labour, 2007).

Simple (nodular) silicosis is mostly found in workers that are in the sandblasting, quarrying, stone dressing, refractory, manufacturing or foundry occupations. This is the most common form of chronic silicosis and it is characterised by the presence of rounded fibrous nodules in the lung. These nodules are usually 1-6 mm in diameter and as a rule the maximum diameter does not exceed 1 cm (Stanton *et al.*, 1999; White, 2001). If larger nodules are found, the classification shifts to "complicated pneumoconiosis". Many of the patients with simple silicosis are asymptomatic and usually without respiratory symptoms or impaired lung function (Mossman & Churg, 1998; White, 2001). In simple silicosis the fibrotic lesions appear in the upper and middle lung zones, but primarily in the upper zones. When the lower zones are involved or infected, this usually indicates a severe case (Mossman & Churg, 1998; Stanton *et al.*, 1999; White, 2001).

Complicated silicosis is also known as PMF or "conglomerate silicosis", which refers to the larger lesions formed in the lungs, as the silicotic nodules are increased in size and have coalesced and agglomerated into lesions of larger than 1 cm in diameter (Stanton *et al.*,1999; Castranova & Vallyathan, 2000; White, 2001; Weissman & Wagner, 2004). A compromise of the lung function usually goes hand in hand with a mixed restrictive or obstructive pattern, but pure restriction or obstruction can be found separately (White, 2001).

2.5.1.2 Acute silicosis

Acute silicosis is also known as "silicoproteinosis", which name has its origin in the distinguishing feature of the intra-alveolar deposits found in acute silicosis. These deposits are similar to those seen with alveolar proteinosis, hence the origin of the second name (Stanton *et al.,*1999; Rees & Murray, 2007). The air spaces are filled with thick proteinaceous material that consists of fluid and cells and the result is radiological changes because the alveolar surfactant is compromised (Stanton *et al.*,1999; Castranova & Vallyathan, 2000; Rees & Murray, 2007). Diffuse interstitial fibrosis is not found in this form of silicosis (Stanton *et al.*, 1999). Acute silicosis reactions appear within a few weeks to two to five years after initial exposure of exceptionally high concentrations of crystalline silica (Stanton *et al.*, 1999; Castranova & Vallyathan, 2000). Exposure to very high silica dust levels is mainly found where workers produce finely ground silica (silica-powder workers), especially where the material is sandstone or other material with a high silica content. These occupations include sandblasting, rock/surface drillers, tunnellers, silica flour milling, ceramic making and grinding (Stanton *et al.*, 1999; Castranova & Vallyathan, 2000; Stanton *et al.*, 2006; Department of Labour, 2007).

2.5.1.3 Accelerated silicosis

Accelerated silicosis develops with rounded nodular lesions in the upper lung zones, which is a pattern very similar to that of simple silicosis. Accelerated silicosis is the result of inhaling very high concentrations of silica dust over a relatively short period of about five to ten years. The time from initial exposure to the onset of the disease is a relatively short time period (the nodules develop sooner) and the progression to complicated silicosis is much faster (Montana Department of Labor Industry, 2002; Stanton *et al.*, 2006; Rees & Murray, 2007). Occupations associated with accelerated silicosis are silica flour mill operations, blasting and other mechanical and crushing operations (Castranova & Vallyathan, 2000; Department of Labour, 2007).

2.5.1.4 Symptoms of silicosis

Silicosis can remain free of symptoms for about ten to 20 years after silica exposure and thus silicosis patients are usually asymptomatic (White, 2001; Ross & Murray, 2004; Stanton *et al.*, 2006). As the disease progresses, breathing may become harder and in severe cases dyspnoea (breathlessness) is found, usually during exercise and only when extensive fibrosis of the lungs is present, such as is found during PMF and TB (Ross & Murray, 2004; Stanton *et al.*, 2006; Department of Labour, 2007). The breathlessness may also reflect an associated airway disease such as chronic bronchitis (Ross & Murray, 2004; Department of Labour, 2007; Rees & Murray, 2007). Symptoms of silicosis are very contradictory, but the common symptoms include the production of a cough and sputum. These symptoms are usually related to chronic bronchitis, but the development of TB or lung cancer can also be reflected by these symptoms (Ross & Murray, 2004; Rees & Murray, 2007). Systemic symptoms such as haemoptysis, weight loss, fever and any new radiographic features are also characteristic of silicosis (Montana Department of Labor, 2002; Ross & Murray, 2004; Rees & Murray, 2007). Patients with silicosis have an increased risk for extra-pulmonary tuberculosis and this risk is usually higher with established silicosis (White, 2001; Ross & Murray, 2004).

2.5.1.5 Diagnosis of silicosis

Chest x-rays, lung function tests, sputum analysis and lung biopsies, as well as the work history of the patient (worker), are all part of the diagnostic procedure for detecting silicosis (Stanton *et al.*, 2006; Department of Labour, 2007; Rees & Murray, 2007).

Chest x-rays are the means of detecting silicosis the earliest. This is also the most reliable method as the presence of fibrous tissue is shown on these x-rays. Taking lung function tests is not that reliable, as changes in lung function tests are not found when silicosis is diagnosed.

The lung function tests are performed by using a spirometer that assesses the performance of the lungs (Workers Health Centre, 2004; Department of Labour, 2007).

By determining the patient's work history, silicosis can be differentiated from other dust-related diseases that have the same or similar symptoms and formations, such as asbestosis, TB, sarcoidosis and histoplasmosis (Workers Health Centre, 2004; Rees & Murray, 2007; Department of Labour, 2007).

Biomarkers are biological measurable indicators or products that result from physiological processes that represent a critical step in the development of toxicity. These biomarkers are showing promise as a diagnostic tool for silicosis. Blood, urine, sputum or saliva are all sources of specific biomarkers. Selectivity plays an important role between the concentration of a specific peripheral biomarker for a specific organ and associated occupational disease. Using sensitive biomarkers has an advantage, as early changes can be detected at cellular or molecular level (Department of Labour, 2007).

2.5.1.6 Treatment of silicosis

Silicosis is a non-curable occupational disease, but is preventable (Department of Labour, 2004; Ross & Murray, 2004). Currently, the use of therapeutic agents for the treatment of silicosis is an interest and there is also an interest in lung lavage, with the purpose of removing silica from the lungs. The above-mentioned intervention has not yet demonstrated any favourable impact on the progression of acute or chronic silicosis. Smoking cessation programmes have been shown to be particularly important for miners that are exposed to silica. This is because of the adverse effects of smoking and also the interaction between silica exposure and smoking in the development of COPD (Ross & Murray, 2004).

2.5.2 Coal Worker's Pneumoconiosis (CWP)

CWP is the official name of a form of pneumoconiosis in which respirable coal dust particles accumulate in the lungs and cause the lung tissue to darken. More commonly, the disease is known as "black lung disease" because the inhalation of heavy deposits of coal dust makes the miner's lung look black instead of a healthy pink (OSHA, 1987; Castranova & Vallyathan, 2000). CWP or black lung disease is a lung disease associated uniquely with coal and occurs mostly in older workers in the coal industry, caused by the inhalation of small amounts of coal dust over many years (Finkelman *et al.*, 2002).

The total dust burden in the lungs and the coal rank (based on carbon content) are related to the risk of developing CWP (Ross & Murray, 2004). Dust from high-carbon coal (anthracite and bituminous) can cause CWP when it is inhaled chronically. This usually occurs with an exposure period of over 20 years (MERCK, 2005). The greater relative surface area of the coal dust particles, more free radicals on the surface and higher silica content are some characteristics of the higher rank coal that makes them more prone to cause CWP (Ross & Murray, 2004).

Dennison and Mathews (2002) also associate the risk of developing CWP with factors such as the duration of the exposure, usually 15 years or longer; the intensity of this exposure (dust count and particle size); the location of the mine; the silica content of the coal; and also the susceptibility of the worker.

When the coal dust is inhaled, it is engulfed by alveolar macrophages and inflammation is stimulated through the release of cytokines, which leads to the collection of coal dust in the lung interstitium around the bronchioles and alveoli, referred to as “coal macules” (MERCK, 2005). The size and toxicity of inhaled particles determine the site of damage in the lung (Fishwick, 2004). Collagen accumulates and causes coal nodules to develop. The bronchiolar walls now weaken and dilate, causing focal emphysema. Usually fibrosis is limited to the areas adjacent to the coal nodules and deformation of lung architecture, obstruction to airflow and functional impairment occur mildly, but in a subset of patients the above mentioned can be destructive. There is a similarity between coal-induced PMF and conglomerate silicosis, but the development of PMF in coal workers is unrelated to the silica content of coal (MERCK, 2005). The fibrosis associated with exposure to coal dust is significantly less extensive and intense than the fibrosis caused by more bioactive dusts like silica and asbestos (Ross & Murray, 2004).

The intensity of dust exposure, age, inhaled silica content in the dust and silica’s surface bioactivity, individual immunological factors and the presence of TB are all factors that determine the presence and stage of CWP as well as the development of PMF (Ross & Murray, 2004). Two forms of CWP are found: simple CWP and complicated CWP (Castranova & Vallyathan, 2000; Fishwick, 2004; Ross & Murray, 2004).

2.5.2.1 Simple CWP

Simple CWP is asymptomatic and in this form of CWP individual black dust coal opacities are centred in the respiratory bronchioles. This usually occurs in the upper zones of the lung (Castranova & Vallyathan, 2000; Dennison & Mathews, 2002; MERCK, 2005). The size of these opacities usually ranges from 1-6 mm in diameter and they are irregular in size (Castranova & Vallyathan, 2000; Dennison & Mathews, 2002). When seen through a microscope, the macules contain coal dust-laden macrophages that have a fine network of reticulin and some collagen fibres. These macules are also associated with focal emphysema, but they have not been associated with pulmonary symptoms (Castranova & Vallyathan, 2000).

2.5.2.2 Complicated CWP

Complicated CWP is also known as PMF and occurs when the disease has progressed. Signs associated with complicated CWP include progressive exertional dyspnea; a productive cough with milky, grey, clear or coal-flecked sputum; and barrel chest and hyper resonant lungs with dull areas, diminished breath sounds, crackles and wheezes. Chest x-rays show one or more large opacities of one to five centimetres that form conglomerate masses of dense tissue in the lungs (Dennison & Mathews, 2002).

2.5.2.3 Symptoms of CWP

As a rule CWP itself does not cause symptoms or physical signs and most of the chronic pulmonary symptoms that occur are caused by other conditions, such as industrial bronchitis from coal dust or coincident emphysema from smoking (Ross & Murray, 2004; MERCK, 2005). A chronic cough, coughing blood, chest pain and weight loss may be detected and may cause problems in patients even after they have left the workplace and do not smoke (MERCK, 2005; Stanton *et al.*, 2006).

Respiratory symptoms of higher grades of PMF include severe airway obstruction, restrictive defects, abnormalities in ventilation and perfusion, a reduction in diffusing capacity and also low arterial oxygen pressure. These changes are progressive and the eventual result is pulmonary hypertension or cor pulmonale (Castranova & Vallyathan, 2000), which is an enlargement and strain of the right side of the heart that is caused by chronic lung disease. Cor pulmonale is only the result in severe cases and may lead to right-sided heart failure. In rare cases melanoptysis (black sputum) is seen, which is caused by the rupture of PMF lesions into the airways (MERCK, 2005).

2.5.2.4 Diagnosis of CWP

Diagnosing black lung disease starts with a history check and chest x-ray. The chest x-ray will reveal small spots which are caused by the collection of coal dust around the respiratory bronchioles that lead to the alveoli (Stanton *et al.*, 2006). Performing a pulmonary function test may help with the diagnosis, as a loss of forced expiratory volume in the lungs of patients has been found (Ross & Murray, 2004).

2.5.2.5 Treatment of CWP

CWP is not curable and no treatment exists for this disease, so prevention is the only solution (Stanton *et al.*, 2006). Complications, however, can be treated, such as lung infections, airways obstruction and cor pulmonale. Coal dust exposure must be stopped immediately after the disease has been detected and then be integrated with an adequate health surveillance programme that includes lung function tests and periodic radiology (Fishwick, 2004). In simple CWP, treatment is rarely necessary, although recommendations include cessation of smoking and TB surveillance. When a patient has pulmonary hypertension and/or hypoxemia they are given supplemental oxygen therapy and the more severely affected workers can be assisted by pulmonary rehabilitation to perform daily activities. Although the disease is not curable, it may be prevented by eliminating exposure, cessation of smoking and also providing pneumococcal and influenza vaccinations (MERCK, 2005).

2.6 Other Diseases associated with Silica Exposure

2.6.1 Silicosis, Tuberculosis and HIV

Crystalline silica dust exposure causes a variety of diseases, of which silicosis and silica dust-associated TB are on top of the list of occupational health priorities in low-income countries and are still found in some high-income countries (Rees & Murray, 2007). According to Schoeman and Schröder (1994), one of the clinical features of silicosis is an increased susceptibility to TB. Cowie (1994) supported this statement when he documented that during his study the relative risk for TB for men with silicosis was 2,8% when compared with the prevalence of TB in men without silicosis. His study involved a cohort of 1 153 older gold miners with and without silicosis who had not contracted TB. They were followed for seven years by a routine mine surveillance programme for the detection of TB. He found that the TB incidence increased from 1% per annum for men that did not have silicosis to 2,2% per annum for those with mild silicosis, 2,9% per annum for those with moderate silicosis and 6,3% for those miners with advanced silicosis. Recent studies indicate that it is not just silicosis but silica itself that creates an increased risk for TB. This risk persists even after exposure has ended (Department of Labour, 2004; Rees & Murray, 2007). The HIV (human immunodeficiency virus) epidemic aggravates the prevalence of silica-related TB in low-income countries. When the risks of silicosis and HIV infection are combined, they act multiplicatively, and the result is that TB remains a silica-related occupational disease in non-HIV-infected miners just as much as in infected miners (Corbett *et al.*, 2000; Donoghue, 2004; Rees & Murray, 2007).

2.6.2 Cancer

The International Agency for Research on Cancer (IARC, 2007) classified crystalline silica as Class 1, classifying it as carcinogenic to humans. This means that there is sufficient evidence of carcinogenity in humans. Crystalline silica has been classified as Class 1 by the German MAK Commission. This defines it as a substance that causes cancer in man and one that can be assumed to make a significant contribution to cancer risk. The German MAK Commission also state that epidemiological studies provide adequate evidence of a positive correlation between human exposure and the occurrence of cancer (MAK, 2007). NIOSH, in its turn, classifies crystalline silica as a potential occupational carcinogen with no further categorisation (NIOSH, 2002). Crystalline silica is known to be a human carcinogen by the U.S. National Toxicology program (NTP), which states that sufficient evidence exists from human studies to indicate a casual relationship between exposure and human cancer (NTP, 2005). The ACGIH classifies crystalline silica as A2 (suspected human carcinogen), stating that human data is accepted as adequate in quality, but is insufficient or conflicting for classifying the agent as a confirmed human carcinogen. This classification is used primarily when there is sufficient evidence of carcinogenicity in animals with relevance to humans, but limited evidence in humans (ACGIH, 2008).

Silica is classified as being a human carcinogen. Smoking's combined effect with silica exposure also has to be taken into consideration, but with silica there is little and insufficient data to state with confidence the nature of the interaction between silica exposure and smoking. Free (crystalline) silica is of most concern for cause of cancer and currently no evidence exists that amorphous silica causes lung fibrosis or cancer. Silica particles induce a very strong immunologic response in the lung and they have a toxicity to macrophages, and these two consequences release a variety of substances such as lysosomal enzymes that can promote fibrosis, but also cancer. A stronger association is found in the evidence for lung cancer in workers with silicosis. When looking at the data, there are two possible causes for the observed excess lung cancer risk. These are: (1) the relatively high doses of silica that cause silicosis can then result in lung cancer, and (2) there are some aspects of the fibrotic disease that can account for the excess lung cancer risk. The data to determine which of the above-mentioned is the main cause is insufficient.

As a conclusion one can summarise that the evidence of the studies of silica-exposed workers is not consistent, although the studies do suggest an increased lung cancer risk. The exposure-response analysis of these studies is also not consistent. Despite the inconsistency, there is a tendency that those workers with the highest exposure show the highest risk, and a moderate increased risk is seen in silica-exposed cohorts in general (Steenland & Stayner, 1997).

A study that was conducted by Adrian *et al.* (2007) included collecting detailed information on the lifestyle and occupational information of lung cancer cases. The information was collected from 2 852 newly diagnosed cases of lung cancer and 3 104 controls, between 1998 and 2002 in seven European countries. Local experts were used to assess the probability, intensity and duration of silica exposure for each job held. The result was that an association between crystalline silica exposure and an increased risk of lung cancer was found, which was most apparent for the upper tertile of cumulative exposure, duration of exposure and weighted duration of exposure. No interaction beyond a multiplicative model between tobacco smoking and silica exposure was observed in this study.

In another study the evidence of a link between silica dust and oesophageal cancer was investigated (Yu *et al.*, 2005). The cohort consisted of all newly diagnosed cases of silicosis (caisson and non-caisson workers) at the Pneumoconiosis Clinic of the Tuberculosis and Chest Service of the Department of Health in Hong Kong between January 1, 1981 and December 31, 1998. In this study, the researchers adjusted for cigarette smoking as well as alcohol drinking. Their conclusion was that the best explanation for the excess risk of oesophageal cancer mortality in the caisson workers with silicosis was due to the very heavy exposure of these workers to free silica dust in their work environment (Yu *et al.*, 2005).

2.6.3 Autoimmune Diseases

Some systemic autoimmune diseases occupational silica exposure has been associated with are scleroderma, rheumatoid arthritis, systemic lupus erythematosus and also some of the small vessel vasculitidies with renal involvement (Parks *et al.*, 1999; Cooper *et al.*, 2002; Calvert *et al.*, 2003; Rees & Murray, 2007). There have also been experimental studies that indicate that silica can, non-specifically, enhance the immune response because it can act as an adjuvant (assisting in antibody production) (Parks *et al.*, 1999; Ding *et al.*, 2002). This is considered one of the mechanisms by which silica might be involved in autoimmune disease development. It can be concluded that silica dust acts as a promoter or accelerator to the development of autoimmune disease and in the end requires another factor to break the immune tolerance or to initiate autoimmunity (Steenland, 2005).

Underlying differences in genetic susceptibility or other environmental exposures can determine the specific manifestation of the above-mentioned effect. Specific occupational groups with high silica exposure levels were examined and these studies showed increased rates of autoimmune disease compared to the expected rates in the general population (Parks *et al.*, 1999). Ding *et al.* (2002) autopsied 325 coal miners with moderate and severe silicosis and 164 miners with no lung disease. They found gene-gene and gene-gene-environment interactions which indicate that inflammatory cytokine polymorphisms modify the development and severity of silicosis.

2.6.4 Rheumatoid Complications

Rheumatoid pneumoconiosis (Caplan syndrome) is normally associated with mild silicosis, although it is rarely found in silicosis cases (Parks *et al.*, 1999; Castranova & Vallyathan, 2000). Characteristic of this disease is rapidly developing large opacities, mostly in the periphery of the lungs, that have a size range of 1-5 cm (Castranova & Vallyathan, 2000). Patients with rheumatoid disease or with a rheumatoid positive factor are the most susceptible to rheumatoid silicotic complications, possibly because of the strong immune response in the lung (Castranova & Vallyathan, 2000; Steenland, 2005).

2.6.5 Vascular Diseases

In silica-induced autoimmune vascular disease, the increase in cytokine production (TNF-α and Inteleukin-1) may be blamed. Adhesion molecule expression elevation on vascular endothelial cells is caused by TNF-α and Inteleukin-1. Adhesion molecules recruit inflammatory cells to specific sites on the vascular epithelium and this interaction may be caused by the vascular pathology that follows silica exposure (Cooper *et al.*, 2002).

In cases of severe acute silicosis, chronic hypoxia is a common cause of death. Pulmonary vascular spasms can occur because of chronic hypoxia, which is the result of severe involvement of the lung parenchyma. A common feature is morphologic alteration of the vasculature and this is caused by the dust accumulation and fibrosis found in PMF (Castranova & Vallyathan, 2000).

2.6.6 Glomerulonephritis

Rosenman *et al.* (2000) describe case reports of severe glomerulonephritis with renal failure that occurs in patients with acute silicosis as *silicon nephropathy*. In this study of Rosenman *et al.* (2000), the researcher confirm findings in previous case reports and epidemiological studies of end-stage renal disease, where an association has been found between kidney disease and silica exposure (Castranova & Vallyathan, 2000). Evidence also exists for accelerated silicosis in renal disease that follows prolonged silica exposure (Donoghue, 2004). Although the epidemiological data on the mechanism by which silica causes kidney disease is conflicting, chronic kidney disease should be seen or considered as a complication of silicosis. Two possible mechanisms by which silica causes kidney disease are considered: an autoimmune effect or direct nephrotoxic effect. Silica's association with focal glomerular disease, as found in a few case reports, is also difficult to ignore (Castranova & Vallyathan, 2000).

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CHAPTER 3

ARTICLE

Guidelines for Authors

Annals of Occupational Hygiene

Guidelines for article

The article should follow the format of: Introduction, Methods, Results, Discussion and Conclusion, and the article length should not exceed 5 000 words, excluding the abstract, references, tables and figures. The article must be prefaced by an abstract of the argument and findings, which may be arranged under the headings: Objectives, Methods, Results and Conclusions. The keywords should be given after the list of authors.

SI units should be used, although their equivalent in other systems may be given as well.

Good quality low resolution electronic copies of figures should be sent with the first submission. The figures should also be clearly identified.

Tables should be numbered consecutively and given a suitable caption and each table must be typed on a separate page. Footnotes to the tables should be typed below the table and should be referred to by superscript lowercase letters.

Only references essential to the development of the argument should be included. References in the text should be in the form of "Jones (1995)" or "Jones and Brown (1995)" or "Jones *et al.* (1995)" for more than two authors. The references in the list at the end of the article should be listed in alphabetical order by name of the first author, using the Vancouver Style of abbreviation and punctuation. ISBN should be given for books and other publications where it is appropriate.

Please note: For the purpose of examination of the mini-dissertation the author, at her discretion, thought it good to report the results more thoroughly and for this reason the number of words in the article exceeds 5 000 words.

THE EVALUATION AND QUANTIFICATION OF RESPIRABLE COAL AND SILICA DUST CONCENTRATIONS: A TASK-BASED APPROACH

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ABSTRACT

Silicosis and coal worker's pneumoconiosis are serious occupational respiratory diseases associated with the coal mining industry and the inhalation of respirable dusts that contain crystalline silica. Silica exposure is an occupational health priority even when exposure has ceased or is below the occupational exposure limit (0.1 mg/m^3).

The objective of this study was to determine the individual contributions of the underground coal mining tasks to the total amount of respirable dust and respirable silica dust concentrations found in this environment. The tasks that were identified were continuous miner (CM) cutting, construction, the transfer point, tipping and roof bolting. Respirable dust sampling was conducted at the intake and return of each task, as well as at the intake and return of the section and the intake airway to the section. The five occupations that perform these tasks were also sampled to determine the personal exposure levels.

Respirable dust concentrations and small concentrations of respirable silica dust were found in the intake airway and intake of the section, indicating that the air that enters the section is already contaminated. The respirable dust-generating hierarchy of the individual tasks was: transfer point > CM right cutting > CM left cutting > CM face cutting > construction > roof bolting > tipping. For respirable silica dust the hierarchy was: CM left cutting > construction > transfer point > CM right cutting. CM face cutting, tipping and roof bolting generated concentrations of below quantifiable levels. The personal exposures also differed and the CM and stamler operators had the highest exposure to respirable dust (3.417 ± 0.862 mg/m^3) and respirable silica dust (0.179 ± 0.388 mg/m^3) concentrations, respectively.

Key words: respirable dust, respirable silica dust, coal mining

INTRODUCTION

Coal is defined as a fossil fuel and as a combustible, sedimentary, organic rock that is mainly composed of carbon, hydrogen and oxygen (WCI, 2005; BESR, 2007). A small proportion of quartz or silicates, usually less than 5%, is found in respirable coal mine dust and these silicates are mostly found in the dirt bands within the coal stratum. The average measured silica content of coal seams in South Africa has been found to be 3.5% (Biffi & Belle, 2003). When the overburden is removed by the miners or when they tunnel through rock to get to the coal that has to be mined, elevated silica dust exposures may occur (Stanton *et al.*, 2006).

A characteristic of silica is that it can be found in a crystalline or cryptocrystalline form and is harmless in this form because it cannot be inhaled. However, when silica dust is generated, for example through construction activities, it can be inhaled by workers (Larson, 2004; Maciejewska, 2008). Quartz is one of the polymorphs of crystalline silica, of which alpha (low) quartz is the most common, naturally found, form of quartz and is also the form of crystalline silica that is primarily released during mining, blasting and construction activities (Lujan & Ary, 1992; Department of Labour, 2007; MSHA, 2008).

The time weighted average-Occupational exposure limit (TWA-OEL) for respirable coal dust is 2 mg/m^3 in South Africa, due regard being given to the crystalline silica content of the dust (South Africa, 2006: 29276).

The frequency and severity of mining-related occupational lung diseases are dependent on the commodities mined, airborne pollutant exposure levels, the period of exposure, co-existing illnesses, environmental conditions and individual susceptibility or lifestyles (Ross & Murray, 2004; Department of Labour, 2007).

Silicosis and coal worker's pneumoconiosis (CWP) are both forms of pneumoconiosis caused by the inhalation of dust, especially respirable dust particles (OSHA, 1987; Stanton *et al.*, 2006; Department of Labour, 2007). These diseases have a strong relationship with the coal mining industry (Castranova & Vallyathan, 2000; Stanton *et al.*, 2006). CWP or black lung disease is uniquely associated with coal and coal mining workers and is caused by respirable coal dust that is deposited in the lungs (Finkelman *et al.*, 2002). Silicosis is caused by the inhalation of respirable dusts that contain free crystalline silica and this disease is characterised by the scarring of the lung tissue (OSHA, 1987; Stanton *et al.*, 2006; Department of Labour, 2007). A clinical feature of silicosis is an increased susceptibility to tuberculosis (TB). Silicosis can also cause the development of cancer, autoimmune diseases, rheumatoid complications, vascular diseases and glomerulonephritis (Schoeman & Schröder, 1994; Castranova & Vallyathan, 2000; Cooper *et al.*, 2002; Donoghue, 2004; Yu *et al.*, 2005; Steenland, 2005; Rees & Murray, 2007; IARC, 2007).

The basic types of coal mining operations are surface and underground coal mining (Castranova & Vallyathan, 2000; BESR, 2007). Underground coal miners are exposed to higher levels of coal dust than surface mine workers (Castranova & Vallyathan, 2000). Sixty per cent of the world coal production is accounted for by underground coal mining (WCI, 2005) and the two underground coal mining methods that are most commonly used are room-and-pillar mining (conventional and continuous) and longwall mining (WCI, 2005; Anon., 2006; BESR, 2007).

Room-and-pillar mining consists of a set of entries, between three and eight, that are driven into a coal block and are connected by cross-cuts (splits), at right angles to the entries, forming pillars (WCI, 2005; BESR, 2007). This mining method is divided into conventional- and continuous room-and-pillar mining (Anon., 2006; BESR, 2007). The different operations performed in conventional room-and-pillar coal mining are drilling, undercutting, blasting, loading and roof bolting, performed in sequence to extract coal at the working face (Kissell & Goodman, 2003:23-38; Stanton *et al.*, 2006). A mechanical machine, the continuous miner (CM), replaces all the cutting and loading functions in the continuous room-and-pillar mining method (BESR, 2007).

Cutting and drilling are the two tasks that generate the highest dust concentrations underground in a coal mine (Kissell & Goodman, 2003:23-38; Stanton *et al.*, 2006). Respirable dust particles can also adhere to already cut coal and conveyor belts and become airborne when the already cut coal is handled or experiences vibrations on the moving conveyor belts (Stanton *et al.*, 2006). Another source of dust can be the haulage roads, which are mostly situated in the intake that leads into the mine and its sections. Dust in this area settles out when the particles are big, but when they are crushed, mainly by vehicles' tyres, they become airborne and create a significant dust source (Stanton *et al.*, 2006).

Although literature states that the cutting of coal is one of the activities that contribute the most to the dust concentrations in the underground coal mines, little literature is available on the contribution made by the other tasks also performed. Determining the major dust sources in the underground environment may lead to the implementation of interventions that prevent the high exposures and prevalence of silicosis that are currently experienced.

The aim of this study was to identify the primary dust sources (tasks) within the coal mining industry and to assess and rank these sources according to their contribution to the total amount of respirable dust and silica dust concentrations in the underground environment. The personal respirable coal and silica exposures of the workers performing these activities were also quantified.

METHODS

Study design

As a guideline for performing the dust sampling, the International Methods for Determination of Hazardous Substances 14/3 (MDHS 14/3): "General methods for sampling and gravimetric analysis of respirable and inhalable dust" was used.

Data collection for this study was conducted at a coalmine that was identified as one of the top ten mines that reported the highest personal respirable silica dust exposures to the South African Department of Minerals and Energy (DME) during 2006. For the purposes of this study, one underground production section of the project mine was selected for assessing and comparing the dust level contributions of the individual tasks.

Description of the sampled tasks and occupations

A room-and-pillar method is followed at the project coalmine, consisting of the following tasks: CM cutting, construction, tipping and roof bolting. The transfer point is also situated within the production section.

The continuous miner (CM) is a remote controlled operating machine that cuts the coal for production purposes in one of three directions (face, right or left). Sprayers and a scrubber system are operational for dust control during the cutting process. The full operation of the CM is controlled by the CM operator. The coal is simultaneously and continuously cut and loaded onto the stamlers (shuttle cars), driven by the stamler operators, to be transported to the tipping point, where the coal is pushed from the stamler (tipped) onto the tipping point for further transport on the conveyor belts. The roof bolter operators then move the roof bolter into the area that the CM has last cut to secure the roof, preventing collapse. This is undertaken by drilling holes in the roof that are filled with a cement mixture and the roof bolt. The drilling head is secured with a dust extraction system for dust control.

A miner and couple of cable handlers also perform tasks in the section. The miner's main tasks are to report the production times to the call centre and to ensure that all the tasks underground are performed correctly and according to plan. He also assists with hanging the ventilation curtains. The cable handlers spend most of their time in the close surroundings of the CM, moving the cables around and out of the way while the CM moves to its next cutting position.

The transfer point is a position on the conveyor belt where the coal is transferred from one conveyor belt to the next. The falling distance of the coal is usually 0.5 m to 1 m. Sprayers are situated at these positions along the conveyor belt for dust control.

Construction is represented by belt extension and involves moving the tipping point forward and extending the conveyor belt by adding a new piece. This takes place at least once a week, depending on the production of the section.

The intake airway of the mine from the shaft to the production section and the intake and return of the section itself were also studied to determine the quality of the air that enters and leaves the section.

Data collection: Area samples

A sampling train was set up at each sampling position. It consisted of two Gillian Air gravimetric dust sampling pumps, connected to a mixed cellulose ester (MCE) filter with 0.8 µm pore size, supplied by SKC Omega Speciality Division, with a size-selecting non-corrosive cyclone based on the Higgins Dewell (HD) Cyclone model (design) and supplied by SKC attached to it. The filter sizes that were used were 25 mm or 37 mm, depending on the dust concentration expected and duration of the sampling at the respective positions. The pumps were calibrated for a flow rate of 2.2 l/min, according to the instructions of the manufacturer. They were mounted approximately 1.5 m above ground level for the dust samples to be representative of the respirable dust inhaled by the workers. All other activities that could contribute to the dust concentrations were also noted at each sampling position.

Reliable, calibrated equipment was used throughout the study and qualified and experienced people were used to conduct the sampling. Confidentiality of the personal and trial site data was kept a high priority throughout the study. No references to any personal data have been made and ethical clearance is not relevant.

Intake airway

The intake airway sampling was conducted at four positions (positions 1, 2, 3 and 4). Position 1 was situated below the shaft and position 4 just before the intake of the section, representing the quality of the air that collects throughout the intake airway and is carried into the section. Positions 2 and 3 were situated between these two locations. Use was made of 37 mm filters and two sampling trains were situated left and right of the roadway at each position.

Intake and return of the section

A sampling train was mounted at the intake side (IS) and return side (RS) of the section, respectively, and 37 mm filters were used.

Individual tasks

Data collection for each individual task was conducted at the intake air side and the return air side of the tasks, respectively (see Figure 1), referred to as "Position A" (intake) and "Position B" (return) for the remainder of the article. A sampling train was situated at each of these positions during performance of the task, and was connected with 25 mm filters.

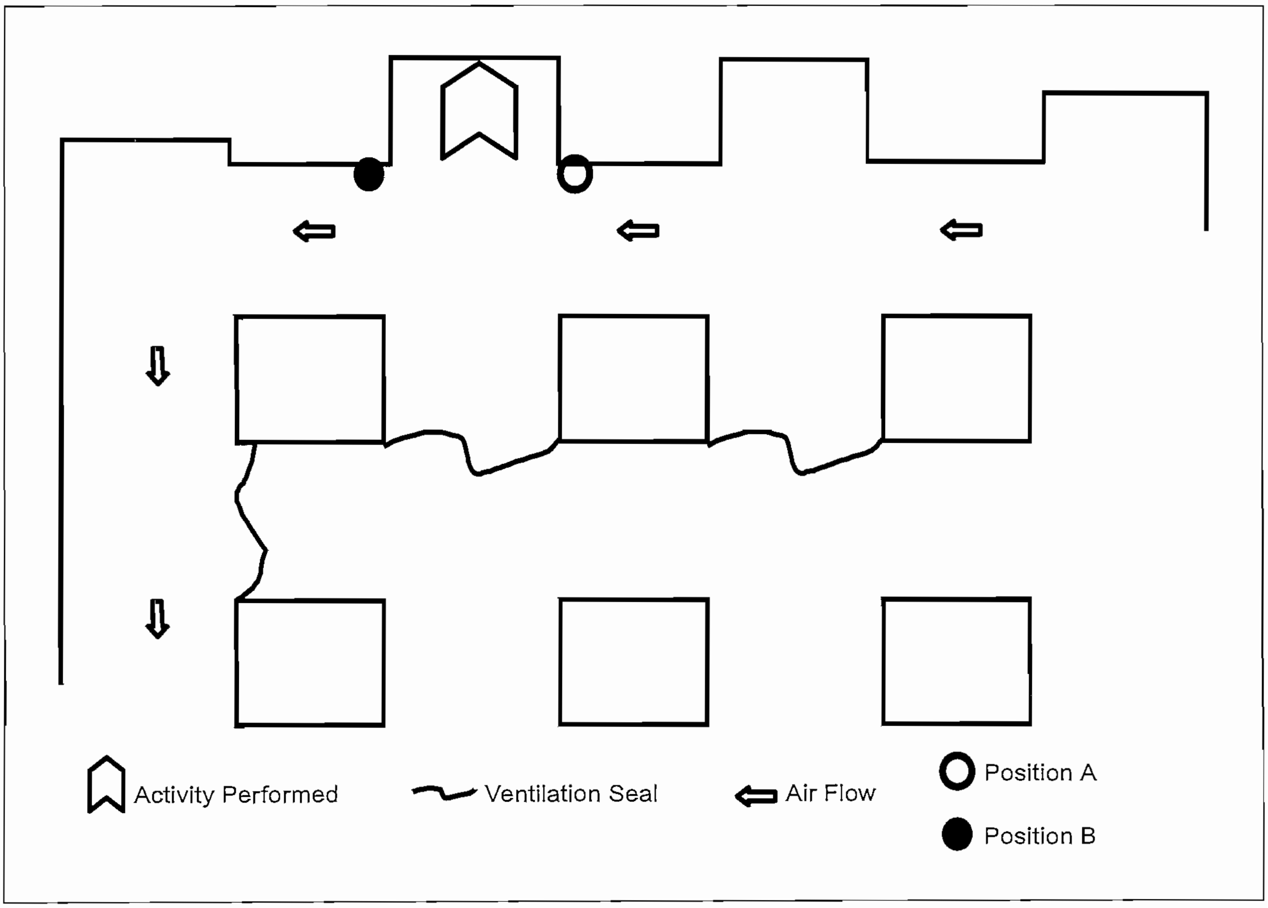

Figure 1: Layout of gravimetric sampling method at different activities performed

Each of the three CM cutting directions was sampled as individual tasks because of different dust concentrations expected at each direction due to the difference in the flow pattern of ventilation during performance of each cutting direction. "Face cutting" refers to cutting the main roadway, or forward; "right cutting" to cutting against the direction of ventilation, and "left cutting" refers to cutting in the direction of the ventilation in the section (see Figure 2).

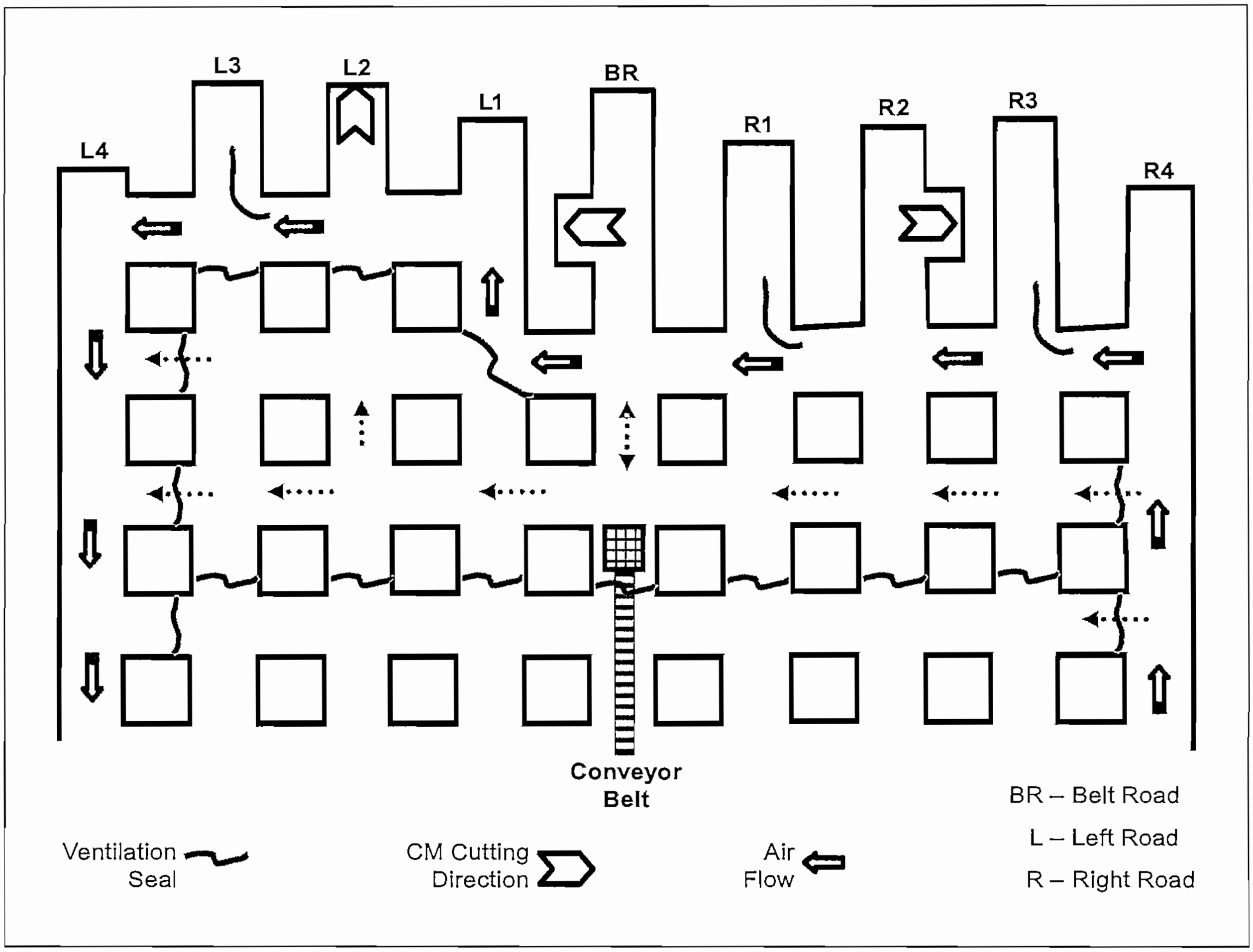

Figure 2: Section layout and CM cutting sequences (where 1=CM face cutting; 2=CM right cutting and 3=CM left cutting)

Data collection: Personal sampling

Personal sampling was performed in the section for the purpose of substantiating the individual task's results. A labour breakdown of the underground mining section was supplied, which consisted of the various occupations present, the identification of the employees, the number of employees per occupation and also the relevant shifts that the employees were working. A total of five occupations are found in the section with nine employees performing these tasks. Each of the following occupations was sampled for three shifts: shuttle car operator (n=9), roof bolt operator (n=6), miner (n=3), CM operator (n=3) and cable handler (n=3).

Each worker was issued with a gravimetric dust sampling pump, positioned on the belt of the worker. The pump was connected with a sampling head (25 mm MCE filter and cyclone attached) by a length of flexible tubing, to be worn throughout the shift period. The sampling head was positioned near the respiratory (breathing) zone of the workers on the collar of their overalls to represent the dust inhaled by the workers during the shift.

Analysis of results

Filters used for sampling were weighed according to the guidelines of the DME: "Guidelines for the gravimetric sampling of airborne particulates for risk assessment in terms of the Occupational Diseases in Mines and Works Act No. 78 of 1973". The gravimetric weighing was conducted with a *Sartorius* R200D balance and the alpha quartz content of each filter was determined using a *Bruker* D8 Advance X-Ray Powder Diffractometer (XRD). For the alpha quartz data analysis the International Standard on alpha quartz analysis, MDHS 101: "Direct-on filter analysis by infrared spectroscopy and X-ray diffraction" was used as a guideline.

Statistical methods

The aim of the statistical analysis was to ascertain whether there are statistically significant differences between the mean respirable dust and silica dust concentrations at positions A and B of the individual activities, the section's intake and return and also between positions 1, 2, 3 and 4 in the intake airway. The significant differences were determined by using t-tests (independent and dependent) as well as analysis of variance (ANOVA). Dependent t-tests were used where all the data points were present and could be paired. Data was excluded when the pump did not function within its acceptable range (post calibration to high or low) and then independent t-tests were used when the data points could not be paired. Analysis of variance (ANOVA) was performed to determine the difference between the individual tasks/activities and their respirable dust or silica concentrations.

Statistical analysis was conducted by using Statistica, version 8 (Stasoft Inc.), and $p<0.05$ was considered to be statistically significant.

RESULTS

Respirable silica dust concentrations of below the detection limit of 0.01 mg/m³ were assigned half the detection limit (0.005 mg/m³) for statistical analysis purposes.

Table 1: Respirable dust concentrations for positions 1 to 4 of the intake airway

Position	N	Mean (mg/m³)	Min (mg/m³)	Max (mg/m³)
Position 1	6	0.090	0.030	0.160
Position 2	3	0.143	0.060	0.280
Position 3	5	0.590	0.410	0.740
Position 4	5	1.004	0.580	1.710

The results shown in Table 1 indicate a gradual increase and thus the presence of respirable dust in the intake airway to the section from position 1 through to position 4. The mean respirable dust concentration increased from position 1 to position 2. The mean respirable dust concentration at position 3 is approximately five times the concentration at position 2, and at position 4 the mean respirable dust concentration is double the concentration at position 3 and approximately ten times the concentration at position 1. An analysis of variance (ANOVA) indicated that the mean respirable dust concentration of position 1 differed significantly from positions 3 ($p=0.0247$) and 4 ($p=0.0003$). Similarly, the respirable dust concentration at positions 2 and 4 also differed statistically ($p=0.0031$).

Table 2: Respirable silica dust concentrations for positions 1 to 4 of the intake airway

Position	N	Mean (mg/m³)	Min (mg/m³)	Max (mg/m³)
Position 1	6	0.005	0.005	0.005
Position 2	3	0.005	0.005	0.005
Position 3	5	0.005	0.005	0.005
Position 4	5	0.016	0.005	0.060

Respirable silica dust concentrations (see Table 2) in the intake airway were below quantifiable levels for all the positions, except position 4, which had a maximum concentration of 0.060 mg/m³.

Table 3: ANOVA statistical results for respirable dust in the intake airway

	N	Position 1	Position 2	Position 3	Position 4
Position 1	6		0.9929	0.0247	0.0003
Position 2	3	0.9929		0.1546	0.0031
Position 3	5	0.0247	0.1546		0.0711
Position 4	5	0.0003	0.0031	0.0711	

Table 4: Respirable dust concentrations for the intake and return of the production section

Activity	Position	Mean (mg/m³)	SD	Min (mg/m³)	Max (mg/m³)	N	p-Value
Section Intake	IS	0.774	0.167	0.496	1.200	16	0.00083
Section Return	RS	2.658	2.017	0.739	9.207	15	

Table 5: Respirable silica dust concentrations for the intake and return of the production section

Activity	Position	Mean (mg/m³)	SD	Min (mg/m³)	Max (mg/m³)	N	p-Value
Section Intake	IS	0.005	–	0.005	0.005	18	0.00081
Section Return	RS	0.028	0.026	0.005	0.107	17	

Mean respirable dust concentrations increased approximately three fold from the intake of the section (IS) to the return of the section (RS) and a statistically significant increase in dust concentrations between these positions (p=0.00083) can be seen in Table 4. Table 5 shows an approximate fourfold increase in mean respirable silica dust concentrations which differ significantly (p=0.00081). This indicates the generation of respirable dust and silica dust in the section.

Table 6: Respirable dust concentrations between positions A (intake side) and B (return side) for individual tasks

Activity	Position	Mean (mg/m³)	SD	Min (mg/m³)	Max (mg/m³)	N	p-Value
CM Cutting Face	A	1.205	0.214	0.890	1.350	4	0.0036*
	B	2.630	0.168	2.410	2.780		
CM Cutting Right	A	1.733	0.875	0.970	2.690	4	0.0029*
	B	4.030	1.311	2.520	5.410		
CM Cutting Left	A	4.400	0.012	4.390	4.410	4	0.0338*
	B	5.935	0.827	4.820	6.810		
Construction	A	1.683	0.602	1.020	2.510	6	0.2037
	B	2.192	0.626	1.710	3.260	5	
Transfer Point	A	1.040	0.235	0.770	1.390	6	0.0039*
	B	5.640	2.214	3.440	9.210		
Tipping	A	1.628	0.491	1.130	2.20	4	0.5152
	B	1.843	0.382	1.420	2.260	4	
Roof Bolting	A	1.360	0.359	0.920	1.70	5	0.0088*
	B	1.916	0.2701	1.55	2.23		

* Indicates statistical significance in respirable dust concentrations between positions as determined by dependent t-test

The amount of respirable dust generated by each individual task was calculated by subtracting the respirable dust concentration at Position A of the task from the respirable dust concentration at Position B of the same task. The difference represents the concentration of respirable dust generated (see Figure 3).

Statistically significant increases (see Table 6) can be seen for all three of the CM cutting directions (face: $p=0.0036$; right: $p=0.0029$; left: $p=0.0338$), transfer point ($p=0.0039$) and roof bolting ($p=0.0088$) tasks between positions A and B. The highest mean respirable dust concentration is observed at Position B of CM left cutting. No statistically significant differences are observed between positions A and B for tipping and construction tasks.

The highest respirable dust concentration was generated at the transfer point (4.600 ± 2.230 mg/m³). The three CM cutting directions follow, with generated respirable dust concentrations of 2.298 ± 0.516 mg/m³, 1.535 ± 0.825 mg/m³ and 1.425 ± 0.343 mg/m³ at CM right, left and face cutting, respectively. Construction and roof bolting generated dust concentrations of 0.665 ± 0.318 mg/m³ and 0.556 ± 0.260 mg/m³, respectively. Tipping has the lowest respirable dust-generating capacity (0.215 ± 0.064 mg/m³). The dust-generation hierarchy is as follows: transfer point > CM right cutting > CM left cutting > CM face cutting > construction > roof bolting > tipping.

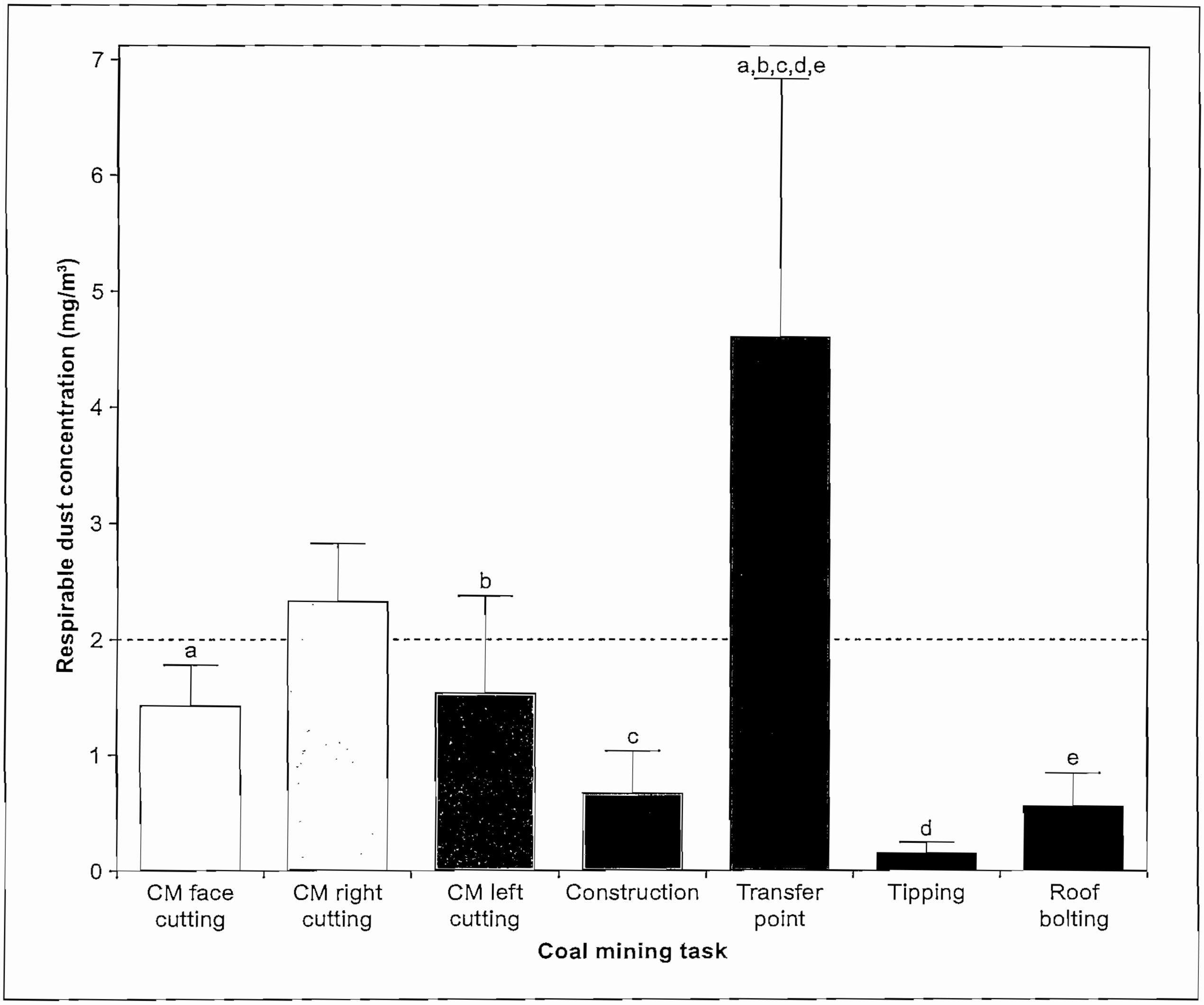

Figure 3: Respirable dust concentrations generated by individual coal mining production tasks (Mean ± SD); "a,b,c,d,e" indicates statistical significant differences

Table 7: Statistically significant differences of respirable dust generated at individual tasks

	N	CM Face Cutting	CM Right Cutting	CM Left Cutting	Con-struction	Transfer Point	Tipping	Roof Bolting
CM Face Cutting	4		0.9270	0.9999	0.9611	0.0108*	0.9145	0.9283
CM Right Cutting	4	0.9270		0.9605	0.4287	0.1083	0.5088	0.3555
CM Left Cutting	4	0.9999	0.9605		0.9279	0.0147*	0.8795	0.8815
Con-struction	4	0.9611	0.4287	0.9279		0.0013*	0.9992	0.9999
Transfer Point	6	0.0108*	0.1083	0.0147*	0.0013*		0.0116*	0.0003*
Tipping	2	0.9145	0.5088	0.8795	0.9992	0.0116*		0.9998
Roof Bolting	5	0.9283	0.3555	0.8815	0.9999	0.0003*	0.9998	

* Indicates statistical significance

Table 7 indicates statistically significant differences between the transfer point and all the other tasks apart from CM right cutting.

Table 8: Respirable silica dust concentrations between positions A (intake side) and B (return side) for individual tasks

Activity	Position	Mean (mg/m³)	SD	Min (mg/m³)	Max (mg/m³)	N	p-Value
CM Face Cutting	A	0.005	-	0.005	0.005	4	-
	B	0.005	-	0.005	0.005		
CM Right Cutting	A	0.005	-	0.005	0.005	3	0.2207
	B	0.058	0.053	0.005	0.110		
CM Left Cutting	A	0.005	-	0.005	0.005	4	0.0469*
	B	0.545	0.331	0.210	0.890		
Con-struction	A	0.093	0.055	0.030	0.180	6	0.0898
	B	0.242	0.184	0.040	0.450	5	
Transfer Point	A	0.005	0.000	0.005	0.005	6	0.0367*
	B	0.062	0.049	0.005	0.110		
Tipping	A	0.005	-	0.005	0.005	4	-
	B	0.005	-	0.005	0.005	4	
Roof Bolting	A	0.005	-	0.005	0.005	6	-
	B	0.005	-	0.005	0.005		

* Indicates statistical significance in respirable silica dust concentrations between positions as determined by dependent t-test

CM left cutting and transfer point tasks had statistically significant increases for respirable silica dust concentrations between positions A and B (see Table 8). The mean respirable silica dust concentrations from Position A to Position B increased approximately hundred times for CM left cutting and approximately nine times for the transfer point. Most of the mean respirable silica dust concentrations at Position A were below quantifiable levels, except at Position A for construction, where a mean respirable silica dust concentration of 0.093 mg/ m^3 was measured.

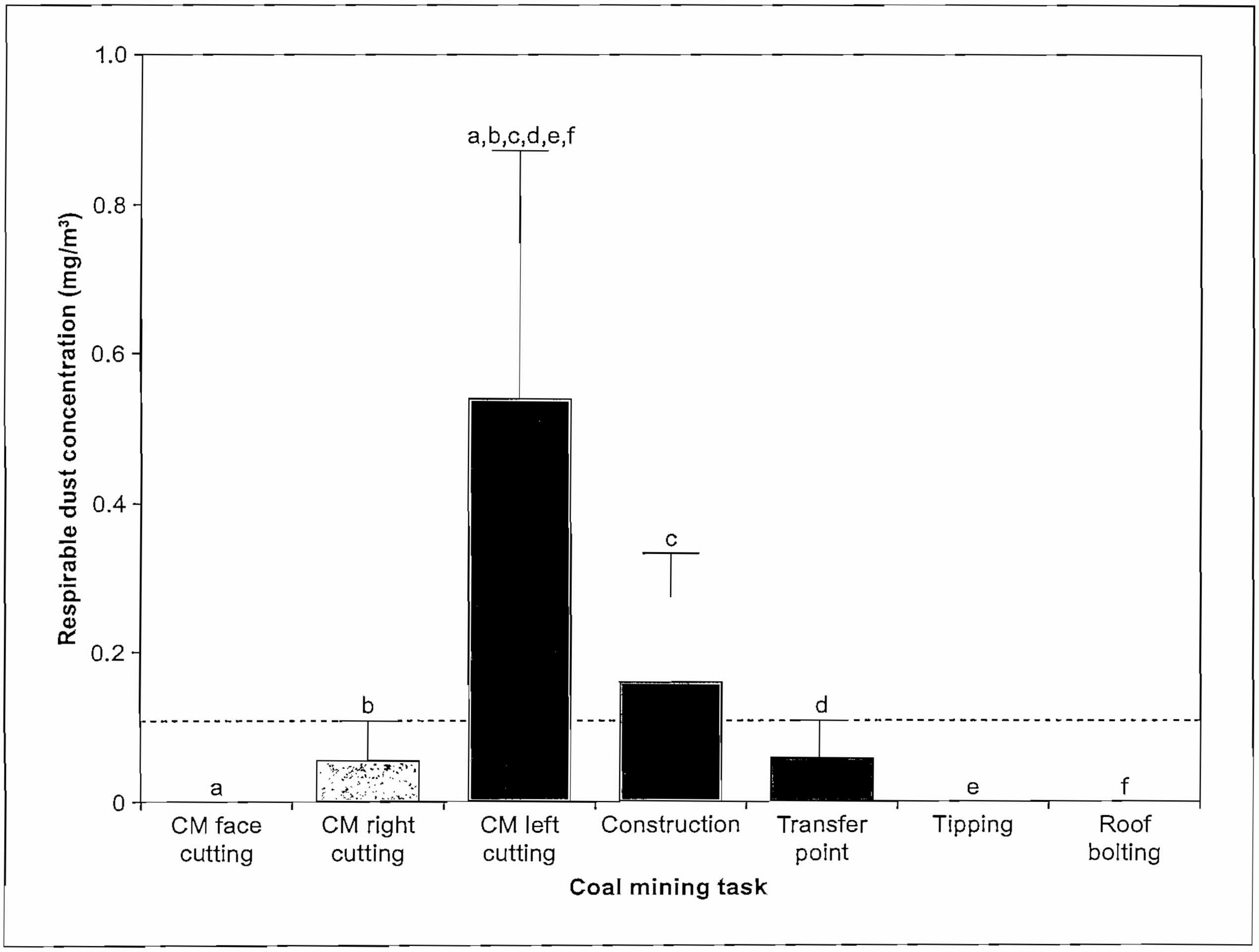

Figure 4: Respirable silica dust generated by the individual coal mining production tasks (Mean ± SD); "a,b,c,d,e,f" indicates significant differences

Figure 4 indicates that CM left cutting generated the highest concentrations of respirable silica dust (0.540 ± 0.331 mg/m^3), followed by construction (0.156 ± 0.170 mg/m^3), the transfer point (0.057 ± 0.049 mg/m^3) and CM right cutting (0.053 ± 0.053 mg/m^3). CM face cutting, tipping and roof bolting indicate no generation of respirable silica dust. CM left cutting differs statistically from all the other tasks (see Table 9).

Table 9: Statistically significant differences of respirable silica dust generated at individual tasks

	N	CM Face Cutting	CM Right Cutting	CM Left Cutting	Con-struction	Transfer Point	Tipping	Roof Bolting
CM Face Cutting	4		0.9992	0.0004*	0.7089	0.9973	1.0000	1.0000
CM Right Cutting	3	0.9992		0.0054*	0.9709	1.0000	0.9997	0.9992
CM Left Cutting	4	0.0004*	0.0054*		0.0129*	0.0013*	0.0136*	0.0004*
Con-struction	5	0.7089	0.9709	0.0129*		0.9191	0.9214	0.5974
Transfer Point	6	0.9973	1.0000	0.0013*	0.9191		0.9996	0.9918
Tipping	2	1.0000	0.9997	0.0136*	0.9214	0.9996		1.0000
Roof Bolting	6	1.0000	0.9992	0.0004*	0.5974	0.9918	1.0000	

* Indicates statistical significance

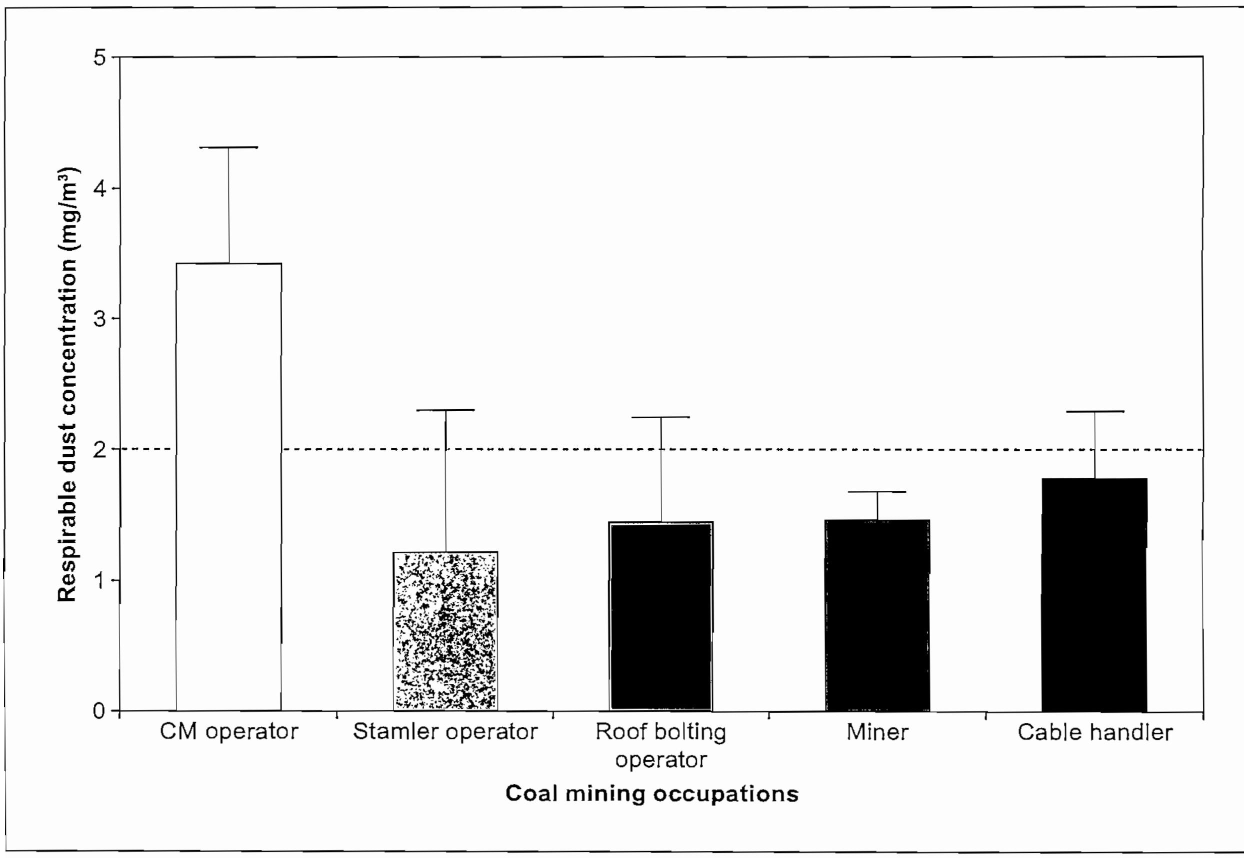

Figure 5: Respirable dust concentrations for personal sampling of occupations in the coal mining production section (Mean ± SD)

The CM operator is exposed to the highest concentration respirable dust (3.417 ± 0.862 mg/m³). The second-highest exposure to respirable dust concentrations exists for the cable handler (1.770 ± 0.495 mg/m³). The other occupations show respirable dust concentrations of above the action level, with the exposure of the roof bolter and miner being 1.428 ± 0.797 mg/m³ and 1.453 ± 0.194 mg/m³, respectively, and 1.207 ± 1.057 mg/m³ for the stamler operator.

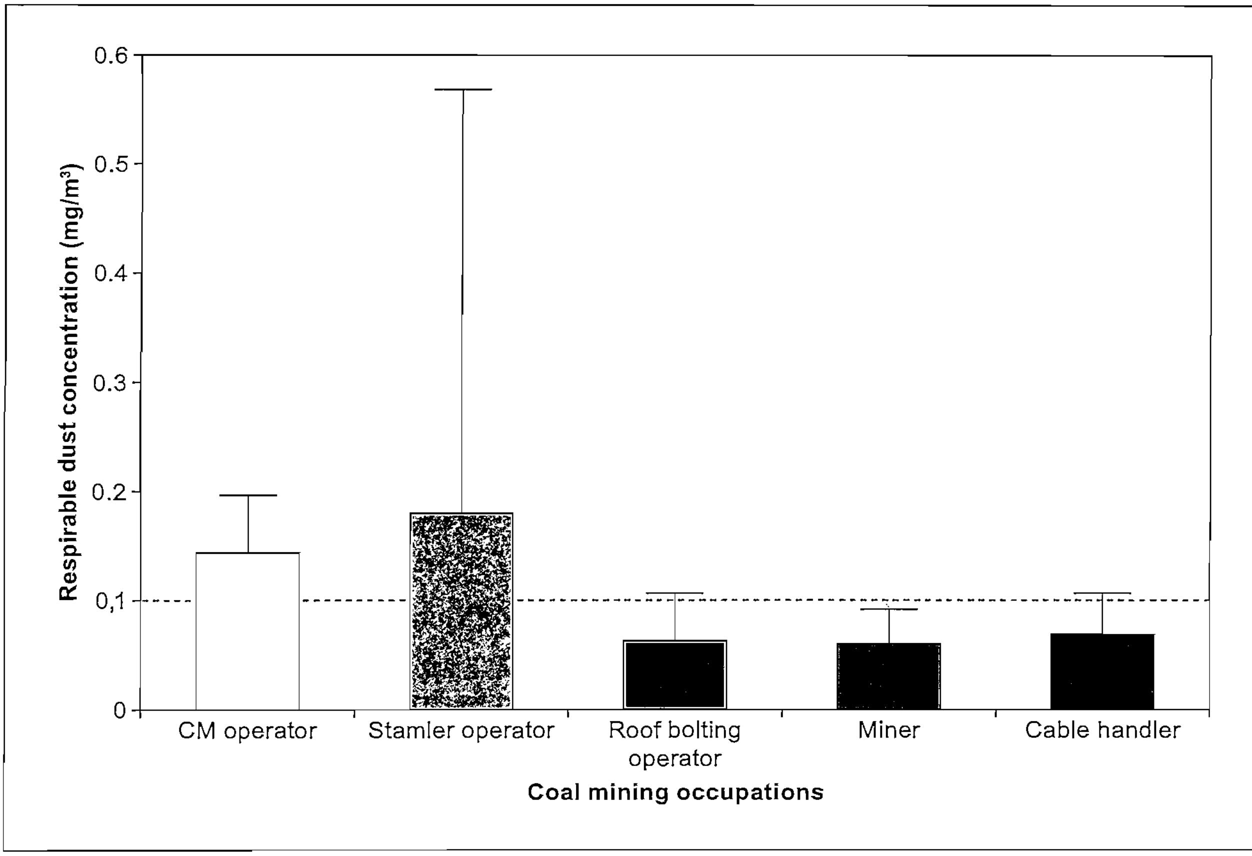

Figure 6: Respirable silica dust concentrations for personal sampling of occupations in the coal mining production section (Mean ± SD)

The stamler operator has the highest respirable silica dust exposure of 0.179 ± 0.388 mg/m³, followed by the CM operator (0.144 ± 0.050 mg/m³). All the other occupations experienced respirable silica dust exposures at below the OEL.

DISCUSSION

Haulage roads are primary sources of dust generation away from the face working area (Kissell & Stachulak, 2003: 83-96; Stanton *et al.*, 2006). The main reason for this is the crushing of the big coarse particles in the haulage roads by vehicles' tyres, creating fine, respirable particles that stay airborne and create a significant dust source in the intakes of the sections (Stanton *et al.*, 2006). The results of the study indicate a gradual increase in the respirable dust concentrations in the intake airway of the mine from the shaft to the intake of the section. Respirable dust is therefore created in the intake airway, with the highest concentrations just before entering the section, delivering concentrations at the action level of respirable dust. Although these concentrations do not exceed the OELs, the danger lies in the fact that the dust in the intake airway delivers already contaminated air to the section even before the other tasks are performed.

Respirable silica dust concentrations were below the quantifiable levels from position 1 through to position 3 in the intake airway and some respirable silica dust was detected at position 4. This may be because the roadway surface between positions 3 and 4 consists of loose coal that can more easily be made airborne by vehicles driving over it, in comparison with positions 1 and 2, where it is compacted.

The respirable dust concentrations at the intake of the section (IS) were below the action level; however, dust in the IS indicates that already contaminated air enters the section instead of the clean, fresh air that is required for ventilation. Mean respirable dust concentrations and individual maximum respirable silica dust concentrations at the return of the section (RS) do exceed their respective OELs during production. Dust and silica dust are therefore generated by the different tasks performed in the section, posing a serious health concern for the workers. Attention to lowering the dust generation at each task could lower the overall dust concentration.

At the face area in a production section, where cutting commences, the CM cutting activity is one of the highest dust-generating sources (Kissell & Goodman, 2003:23-38; Stanton *et al.*, 2006). CM cutting (all three cutting directions) contributed quite significantly to the respirable dust concentrations generated in the underground environment, with CM right cutting exceeding the OEL. This correlates well with the literature findings from Kissell & Goodman (2003:23-38) and Stanton *et al.* (2006). Respirable silica dust concentrations were the highest for CM left cutting, exceeding the OEL approximately five fold. Concentrations at below the action level were observed at CM face and right cutting.

The reason for the differences in respirable dust and silica dust concentrations at the three different cutting directions is not clear, but they may be caused by the cutting sequence followed.

The sequence consisted of first cutting face, then right or left, depending on the direction in which the miners were heading . This sequence only differed when they were situated in the belt road (see Figure 2), where they cut the splits and consequently had to cut the "box" to the left (L1) first to ensure the CM had enough room to be able to turn and cut to the right (R1). Worn bits on the CM cause more dust than when they are still new (Khair *et al.*, 1999; Stanton *et al.*, 2006; Pollock *et al.*, 2009). It was observed that the bits of the CM were not checked and changed after each cut and that no specific routine was followed to replace worn bits either. This may have caused the bits to be worn during cutting in a specific direction, causing more dust generation. Further research is required to determine if this is in fact the cause of the different concentrations measured during cutting in the different directions.

The CM operator was exposed to respirable dust and silica dust concentrations of above their respective OELs. This is a major concern regarding the health of this worker. Kissell and Goodman (2003:23-38) and Goodman *et al.* (2002) explains that high dust levels seen at the remote control operator of the CM are usually the result of his working position. Consequently, he may consider revising his position to spend more time in front of the blowing line curtain. Two individual studies confirm the results when they conclude that between 11% and 12% of their CM operator personal sampling results exceeded 2 mg/m^3 for respirable dust sampled and that between 20% and 30% of the personal respirable silica dust results exceeded 0.1 mg/m^3 for respirable silica dust (Goodman *et al.*, 2002; Goodman, 2009). Goodman (2009) also mentions that the CM operator is one of the occupations with the highest risk of silica exposure.

The cable handlers' personal exposure was expected to correlate with that of the CM operator though their exposures were not as high as that of the CM operator. They do experience the second-highest respirable dust and the third-highest respirable silica dust exposures, both exceeding their action levels. The cable handlers spend most of their time during the shift in the proximity of the CM and downwind from the other tasks in the section where, according to Davitt (2008), they have a high probability of being exposed to respirable silica dust.

Construction does not contribute significantly to the respirable dust concentrations generated underground, although it reveals respirable silica dust levels of above the OEL. This finding could not be explained by literature findings based on belt extension itself. A possible explanation could be the individual activities that are performed within the task, which include drilling, transporting and loading the materials needed for the extension. Davitt (2008) explains that these activities may lead to exposure of the workers to silica dust, although observations show that transporting and loading the materials are not likely to be the main causes. In contrast, hydraulic drilling of the roadway to secure the tipping point could have elevated the respirable dust concentrations generated. Another factor could have been the front loader that is used to assist with the belt extension. The front loader is used to extend the belt by pulling it forward and also to tip loads of coal onto the tipping point and then drive over it back and forth to secure it. This is usually performed at the end of the shift, although the front loader also operates throughout the belt extension shift to scrape the roadways. This cannot be prevented because it is part of the tasks performed during belt extension. The belt extension task itself (assembling the parts and pulling the belt forward) does not visibly cause the generation of high concentrations of dust. Further studies will have to be performed to establish the main cause of dust generated during this task.

According to Kissell (2003: 3-22), dropping the coal at the conveyor belt transfer points from one belt to the next may be a major dust source and dust originates at these points along the conveyor belt. The transfer point generated the highest respirable dust concentration of all the tasks performed underground. No previous studies indicating dust or silica dust concentrations at transfer points could be found for comparison of data.

Dust that adheres to the conveyor belts may become airborne by means of vibration experienced on the belts by the belt rollers or when the rollers crush or pulverise it, releasing respirable dust particles (Kissell, 2003: 3-22; Stanton *et al.*, 2006). This may be a reason for the high respirable dust and silica dust particles observed at this task. Another reason could be the falling distance of the coal from the one conveyor belt to the next, causing high amounts of visible dust to be released when the sprayers are not effective in wetting the coal. Observations revealed that the installed systems were not effective in controlling the visible dust that was released at the transfer point.

The results of this study indicate that the transfer point does not pose a direct health concern to specific workers because this is not usually an occupied area. This area is only occupied when maintenance or a similar task is performed. The belt then usually stands still and the workers are not exposed to the same conditions as when it is operational. The results represent the worst case scenario of the concentrations a worker would experience should he work at a transfer point under production circumstances.

Handling of the coal also takes place at the belt loading point (tipping point) from the shuttle car to the conveyor belt (Stanton *et al.*, 2006). No specific mention is made of the presence of silica at this task in the literature; however, Davitt (2008) mentions that workers operating shuttle cars are prone to be exposed to silica dust.

In this study tippings meant that respirable dust and silica dust concentrations did not exceed the respective OELs; however, some of the samples had maximum concentrations that did. Insufficient ventilation may have caused this, owing to the tipping task being located at the back of the section where the ventilation is split and not channelled as it is in the main roadway. As a result, the amount of dust that is generated at the activity is not removed effectively, causing high dust concentrations to stay airborne, which increases exposure. According to Kissell (2003: 3-22), conveying of the coal by railcar usually generates little dust, but vehicles with rubber tyres (such as the stamlers) will liberate dust if the roadway is dry.

Respirable silica dust concentrations at tipping were all below quantifiable levels, but personal exposures of the stamler operators were approximately double the OEL and their respirable dust exposure was above the action level. The stamler operators are not assigned to the tipping area alone and spend their time underground driving through the section, with a vast amount of time spent in the CM's vicinity while it is cutting and loading the coal. These exposure periods on average are one to two minutes throughout the eight-hour shift. It could be posited that the personal exposures are not only caused by the tipping task, despite high amounts of visible dust present in this area due to the insufficient ventilation. Davitt (2008) supports this when he states that the workers driving shuttle cars (stamlers) and spending time downwind from where the CM is cutting are most likely to be exposed to dust and silica dust. Stanton *et al.* (2006) classify transportation of coal as one of the dust sources underground.

Roof bolting as a task does not generate significant amounts of dust. In contrast, mean respirable dust concentrations at positions A and B do indicate values related to the OEL. Personal respirable dust and silica dust exposures of the roof bolt operators were above their respective action levels. From observations made during sampling, the cause could be the direct result of the CM's cutting. The roof bolter moves directly into the area that the CM has cut last and because this area is not yet well ventilated the dust from the cutting is still visibly present in the air. A study by Goodman & Organiscak (2002) indicated that the dust levels at the bolter intake increased approximately 70 $\mu g/m^3$ when it was operating downwind from the CM and that an increase of approximately 40 $\mu g/m^3$ was seen under the same circumstances for respirable silica dust concentrations. Kissell & Goodman (2003:23-38) do state that high dust exposures of workers on roof bolters can be the result of the CM working upwind of the roof bolter and of the roof bolter consequently working in the dust that the CM generates through cutting (Pollock *et al.*, 2009). Every precaution was taken to sample the roof bolter upwind of the CM so as to isolate the roof bolting task without dust contributions from the CM, but still-high dust levels were observed at the activity.

No research describing personal exposures of the miner has been recorded. Davitt (2008) states that all underground miners (workers) have the risk of being exposed to dust and dust that contains silica. The miner is not assigned to a specific task area in the section. Consequently, his exposure is representative of the dust generated throughout the section. Both the miner's personal exposures to respirable dust and silica dust are above the action levels.

CONCLUSION

The results of this study indicate that the air that collects through the intake airway and enters the section is already contaminated and contributes to the section's overall dust concentration without any tasks being performed.

Individual tasks performed in the section significantly contribute to the total respirable dust concentrations generated in the section, although their contribution towards respirable silica dust concentrations are more moderate. The respirable dust concentrations generated throughout the shift at the return of the section exceeded the OEL for respirable dust with every shift sampled. The dust-generating hierarchy of the individual tasks is: transfer point > CM right cutting > CM left cutting > CM face cutting > construction > roof bolting > tipping. The respirable silica dust-generating hierarchy of the individual tasks is: CM left cutting > construction > transfer point > CM right cutting. CM face cutting, tipping and roof bolting generated concentrations of below quantifiable levels.

Lowering the generation of dust at the individual tasks (the source) will automatically lower the total amount of dust generated.

The hierarchy for personal respirable dust exposures is as follows: CM operator > cable handler > miner > roof bolt operator > stamler operator, and for respirable silica dust: stamler operator > CM operator > cable handler > roof bolter = miner. The personal exposure hierarchy for respirable silica dust is stamler operator > CM operator > cable handler > roof bolt operator > miner.

Dust control methods to lower exposures should include revision of the position of workers with regard to the task performed, positioning of the tasks with regard to the CM cutting and proper use of the line curtains to direct ventilation appropriately. The correct use of respiratory protection should also be encouraged.

In conclusion, the total respirable dust and respirable silica dust concentrations generated underground are determined by the individual tasks performed, with each contribution being unique.

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CHAPTER 4

CONCLUDING CHAPTER

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4.1 Conclusion

As part of the study, the concentrations of respirable dust and respirable silica dust generated by the individual underground coal mining tasks were quantified.

It was determined that the individual underground coal mining tasks contribute differently to the total respirable dust and respirable silica dust concentrations generated in this environment, in this way confirming the research question proposed: Do different activities that are performed in the underground environment contribute differently to the total amount of respirable dust and silica dust concentrations found in this environment?

From highest to lowest, the respirable dust-generating hierarchy of the individual tasks is:

- Transfer point
- CM right cutting
- CM left cutting
- CM face cutting
- Construction
- Roof bolting
- Tipping

The respirable silica dust-generating hierarchy of the individual tasks is (from highest to lowest):

- CM left cutting
- Construction
- Tipping
- CM right cutting

CM face cutting, tipping and roof bolting generated concentrations of below quantifiable levels.

Differences were also observed between the personal exposures to respirable dust and respirable silica dust concentrations of workers. The hierarchy for personal respirable dust exposures is as follows: CM operator > cable handler > miner > roof bolt operator > stamler operator, and for respirable silica dust: stamler operator > CM operator > cable handler > roof bolter = miner. The personal exposure hierarchy for respirable silica dust is stamler operator > CM operator > cable handler > roof bolt operator > miner.

Observations throughout the study revealed that there are numerous factors that could have influenced the respirable dust and silica dust levels that were observed and these should be kept in mind:

4.1.1 CM Cutting

The following factors could have contributed to the dust levels found with continuous miner (CM) cutting:

- The cutting sequence practised was not always the same, and consequently the efficacy of the scrubber box was likely to be impaired since it would have been dependent on a side wall to ensure contaminated air was directed towards the scrubber box;
- The ventilation scoop curtain was not always installed, which can cause ventilation not to be directed into the end;
- While waiting for the full shuttle car to leave and an empty shuttle car to arrive, the CM, together with the scrubber fan and sprays, was often turned off, thereby resulting in airborne dust being liberated into the general atmosphere rather than being sucked into the scrubber fan;
- Stone-dusting activity during the monitoring of a task would result in an increase of mass of the samples, but with airborne matter of little interest. Every effort was made not to conduct sampling during the stone-dusting activity;
- Dry stone dust is disturbed on the footwall into the air by movement of vehicles and becomes airborne, and then contaminates dust samples;
- Blunt coal cutter bits and blocked dust suppression water sprays resulted in high amounts of airborne dust being released;
- Ventilation curtain seals are temporarily opened to allow the passage of vehicles, thereby resulting in short-circuiting of ventilating air and hence less air flowing along the face; and
- During the right cutting task (against the direction of ventilation) the dust was forced through the new holing and past Position A of the task (immediately after the breakthrough to the next roadway), which could be a determining factor in the elevated respirable dust and silica concentrations found at this position.

4.1.2 Construction

The following factors could have affected the dust levels measured:

- The delivery of stone dust in bulk by the front-loader resulted in stone-dust being liberated into the general atmosphere. Dry dust (including stone dust) is liberated from the footwall into the air by movement of vehicles and pedestrians;
- Front loaders scrape the roadways in the section, consequently liberating great amounts of dust, resulting in high dust concentrations;
- The preparation and suspension of stone dust bags were releasing visual stone dust into the atmosphere;
- Actual stone-dusting activity was taking place on the footwall; and
- Ventilation curtain seals are temporarily opened to allow the passage of vehicles and to extend the belt, resulting in short circuiting of ventilating air and consequently less air flowing over the area of the task.

4.1.3 Transfer Point

At the transfer point where the coal is transferred from one belt to the next, the following factors could have contributed to the dust levels observed:

- It was noted that some of the transferred coal was only wet on the surface. During the "transfer" action the coal falls a distance of approximately 0.5 m to 1 m, causing visible amounts of dust to be liberated into the air;
- Dry coal dust exists on the belt system;
- Dust suppression sprays on the transfer point were ineffective or not operating (only wetting the top layer of coal); and
- Dry dust (including stonedust) is liberated from the footwall into the air by movement of vehicles.

4.1.4 Intake Airway

The main factor that could have influenced the increase in respirable dust in the intake airway, especially at positions 3 & 4, could be insufficient footwall treatment in the latter section of the intake airway as opposed to the treatment observed in the beginning section.

4.1.5 Tipping

Possible reasons for the lower respirable dust concentrations generated at the tipping task could be that the freshly cut coal was very wet on the surface and that the coal was only pushed from the shuttle car onto the tipping point, which is more or less on the same level. The effect was that the dryer coal underneath the wet coal was not disturbed. This method is effective, as it is a good means of preventing large concentrations of respirable dust being liberated into the air.

4.1.6 Roof Bolting

A possible explanation for the lower respirable dust concentrations at the roof bolting task could be that the roof bolter is equipped with a vacuum system that extracts air and dust through the drill steel to an onboard dust collection bin during drilling. The vacuum system appeared to be very effective in controlling the dust at source during drilling.

Any elevated dust concentration that was measured during the roof bolting task could have been the result of the CM cutting task, although every effort was made to ensure that the roof bolting task was sampled abovewind of the CM cutting.

4.1.7 Section Intake and Return

The already high respirable dust concentrations found at the intake of the section could be explained by the intake airway study, which indicated that high respirable dust levels already enter the section from the intake airway. This is possibly caused by the dust kicked up on the tractor road in the intake airway by the vehicles (bakkies, front-loaders, tractors etc.) moving on the road during the shift.

The higher dust levels at the return air side of the section is the result of the tasks performed within the section, as the accumulative dust concentration of all the activities leaves the section at the return.

4.1.8 Personal Sampling

Results from the personal sampling could have been influenced by the fact that the workers are not necessarily exposed to dust generated by the task that they are assigned to. The stamler and roof bolt operators are cases in point. The stamler operators tip the cut coal onto the tipping point and from the results it is evident that the tipping task could not elevate the operators' exposures to the levels recorded. This suggests that the other areas that the workers are exposed to and move around in contribute to their exposure levels. In the stamler operator's case the CM is the source of dust. This is because the stamler operator has to stand at the CM for extended periods of time while it is cutting in order for the CM to load the cut coal directly onto the stamler for transport to the tipping point.

Roof bolting does not generate the concentrations of respirable dust that the worker is exposed to, but operating downwind of the CM while it is cutting causes the roof bolt operator to be exposed to the dust generated by the CM cutting task.

4.2 Recommendations for Dust Control

In conclusion, to control respirable dust and respirable silica dust concentrations generated in the underground environment as well as personal exposures to these dusts, it is recommended that the sources of dust generation be controlled. Some suggestions are outlined below.

The CM cutting sequence should be designed to work optimally with the ventilation. Care should be taken to let the dust leave the area without passing the workers and to replace the worn bits on the CM regularly to reduce dust generation caused by worn bits.

The efficacy of the on-board dust scrubbing system on the CM should be improved and it should not be switched off during production.

Ventilation control curtains should be continuously brought forward as the mining progresses and new holings are established, to focus it on the tasks performed and maximise dust control by means of dust removal and dilution. This should especially be enforced at the roof bolting task operating areas.

Dust control treatment on the roadways in intake airways should be effectively applied, especially in the area before entering the section. This will ensure that airborne particles in the intake airway are captured before they enter the section, leaving the section's intake air clean.

Table 1: Respirator selection when exposed to respirable crystalline silica dust

Exposure	Respirator Recommendation
0.5 mg/m³	95 XQ
1.25 mg/m³	PaprHie/Sa:Cf
2.5 mg/m³	100F/Papr THie
25 mg/m³	Sa:Pd,Pp
Emergency	ScbaF:Pd,Pp/SaF:Pd,Pp:AScba
Escape	100F/ScbaE
*Table taken from *NIOSH Pocket Guide to Chemical Hazards*, Table 3, p xx-xxiv	

Table 2: Symbols, code components and codes used for respirator selection

Symbol/Code components/Codes	Description
95XQ	Any particulate respirator equipped with an N95, R95 or P95 filter (including N95, R95 and P95 filtering face pieces), except quarter-mask respirators. The following filters may also be used: N99, R99, P100, N100, R100, P100.
100F	Any air-purifying, full-face piece with an N100, R100 or P100 filter
PaprHie	Any powered air-purifying respirator with a high-efficiency particulate filter
PaprTHie	Any powered air-purifying respirator with a tight fitting face piece and a high-efficiency particulate filter
Sa:Cf	Any supplied-air respirator operator in a continuous-flow mode
Sa:Pd,Pp	Any supplied-air respirator operated in a pressure-demand or other positive-pressure mode
SaF:Pd,Pp:AScba	Any supplied-air respirator that has a full-face piece and is operated in a pressure-demand or other positive-pressure mode in combination with an auxiliary self-contained breathing apparatus operated in pressure-demand or other positive-pressure mode
ScbaE	Any appropriate escape-type, self-contained breathing apparatus
ScbaF:Pd,Pp	Any self-contained breathing apparatus that has a full-face piece and is operated in a pressure-demand or other positive-pressure mode
*Table taken from *NIOSH Pocket Guide to Chemical Hazards*, Table 3, p xx-xxiv	

Dust at the transfer points could be controlled by improving and maintaining the dust suppression water spray systems at these points to wet the coal appropriately; the transfer point could be enclosed; and the top and bottom belts should be wet so that dust sticks onto the belts and is not liberated into the air.

Dust control methods to lower personal exposures should include revision of the position of workers with regard to the task performed, positioning of the tasks with regard to the CM cutting and proper use of the line curtains to direct ventilation appropriately.

The correct use of respiratory protection should also be encouraged. In the *NIOSH Pocket Guide to Chemical Hazards* no recommendations are made for the use of respirators during exposure to coal dust. However, recommendations are made for the use of respirators when exposed to respirable crystalline silica, and these are included in Table 1 and explained in Table 2.

4.3 Recommendations for Future Studies

Recommendations for future similar studies could include the collection of more samples of the tasks performed for enough data for statistical analysis and the sampling of the different scenarios to compare the data. For example, the roof bolting task could be sampled upwind and downwind of the CM cutting task to compare the contribution of the CM cutting's dust generation to the dust concentrations experienced by the roof bolter.